VOLUME 104 PART A NUMBER 13 FEBRUARY 1957

The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

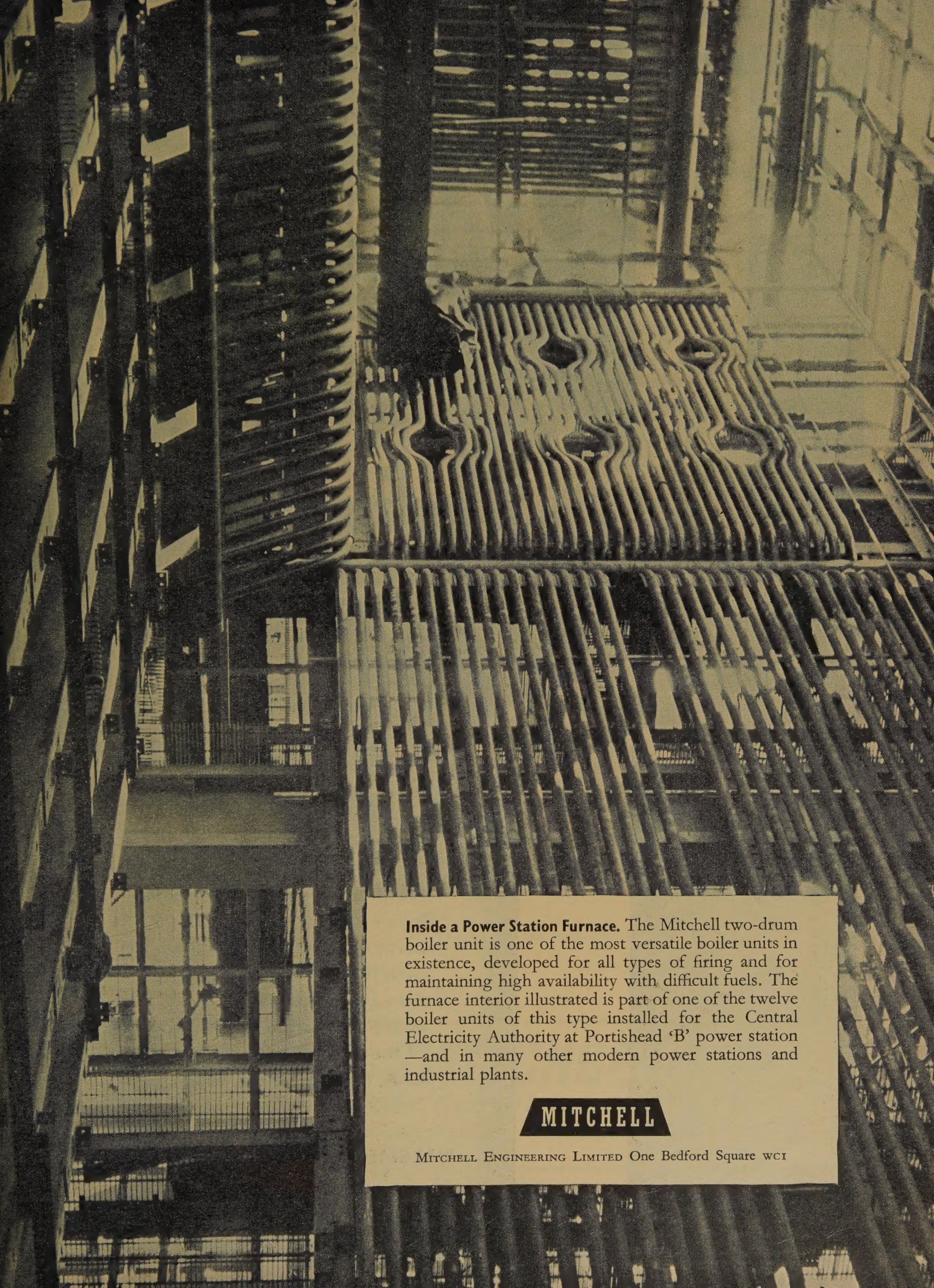
POWER ENGINEERING

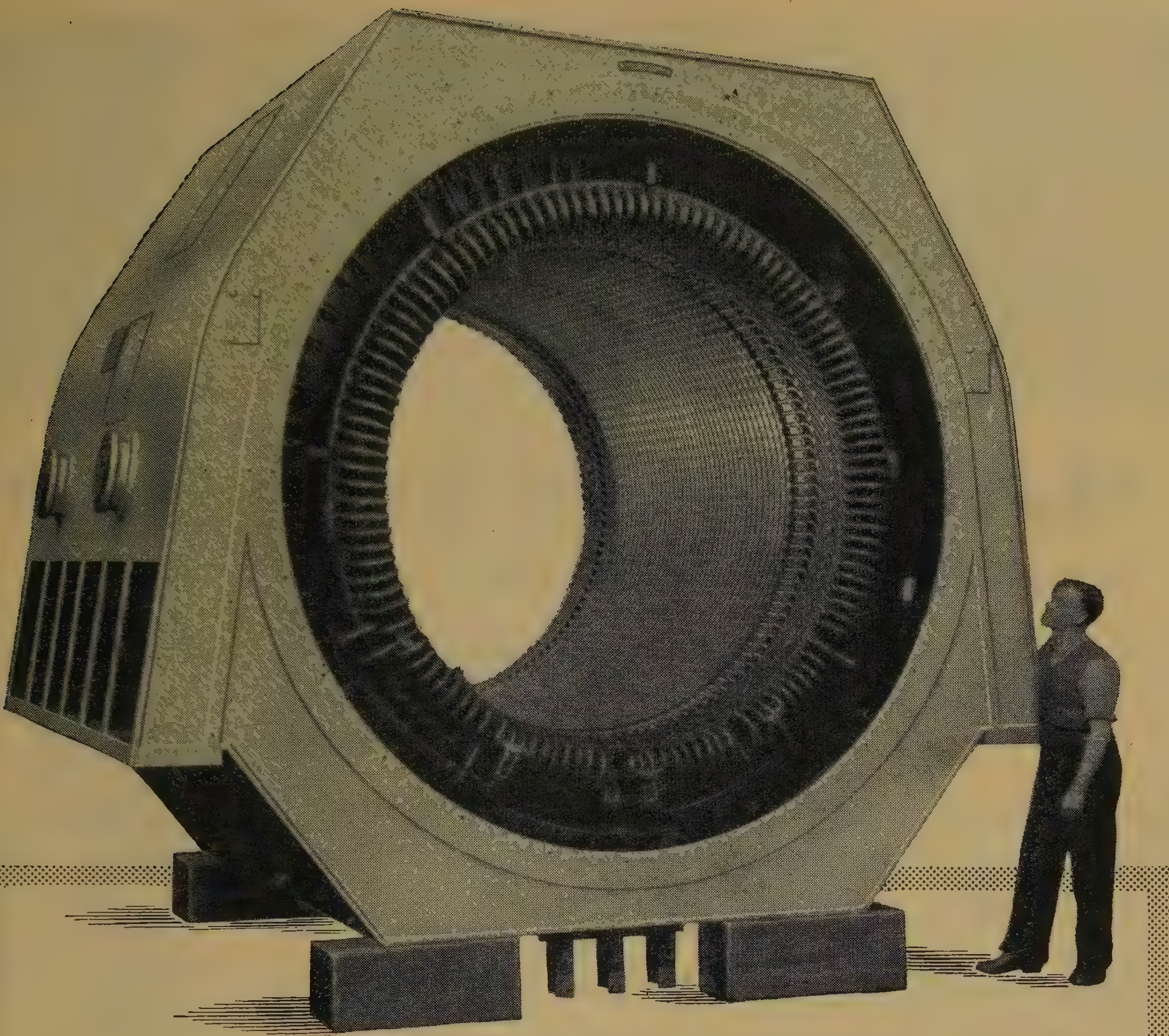
SAVOY PLACE · LONDON W.C.2

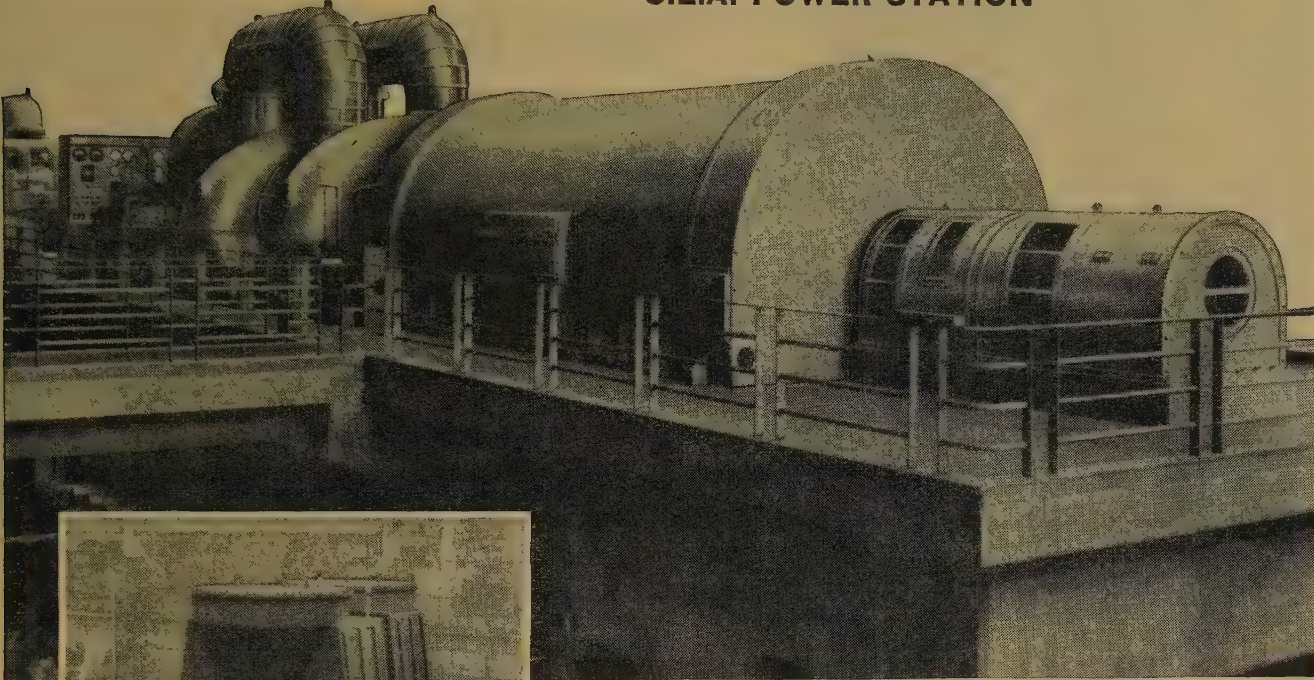
Price Ten Shillings

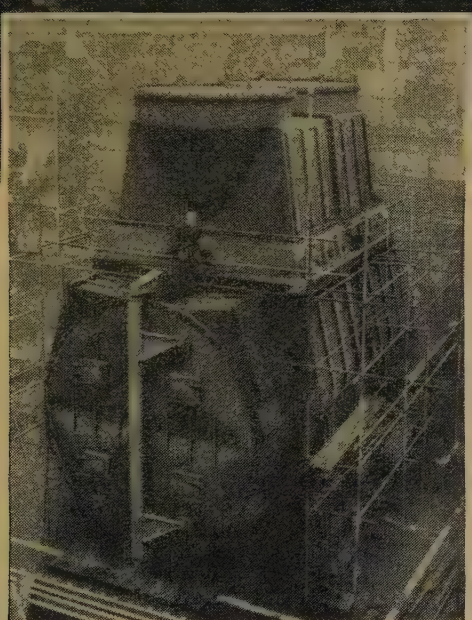
THE INSTITUTION OF ELECTRICAL ENGINEERS

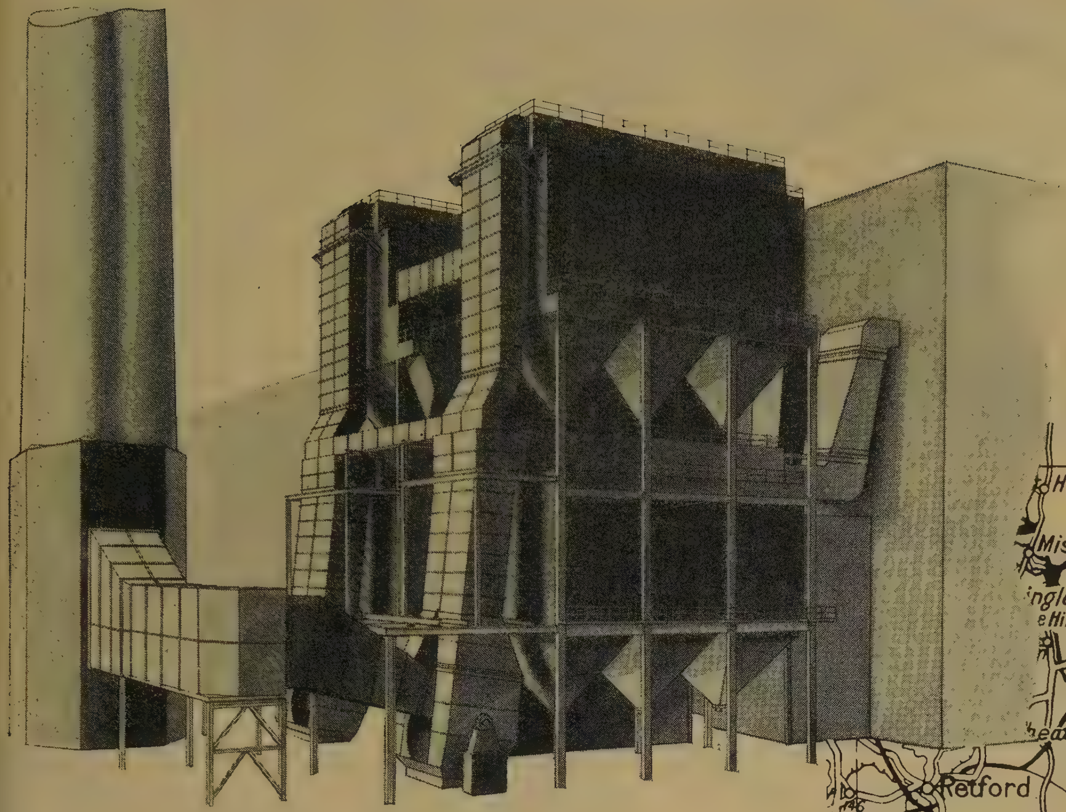
FOUNDED 1871 INCORPORATED BY ROYAL CHARTER 1921












Scotter
Haxey
R. Trent
Kirton
Misterton
Blyton
Corringham
Gainsborough
Lea
Retford
Scampton
Saxilby
E. Drayton
Tuxford
E. Markham
HIGH MARNHAM
Ollerton
Bracebridge
Ossington
Carlton
Collingham
Fosse Way
Kirklington
Kelham
R. Witham
Brant Broughton
Southwell
Newark
Beckingham
Epperstone
E. Stoke
E. Bridgford
Long Bennington
Whatton
Bottesford
Grantl

BROOKHIRST
MOTOR CONTROL ACCESSORIES

1

2

3

A very wide variety of control devices such as push-button stations, control switches, main current switches and limit switches is offered in the Brookhirst standard range. These fine quality units are manufactured on a batch production basis and are normally under stock control and available on very short delivery.

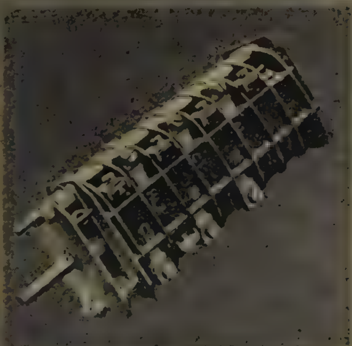
The illustrations show:

(1) An 'Isofuse' Switch/Fuse unit.
(2) Snap action shunt limit switch.
(3) Two-point push button.
(4) Single-pole Rotary switch.
(5) F.H.P. Open-type starter.
(6) Heavy-duty Rotary switch.
(7) Joystick control switch.
(8) Main current reversing switch.

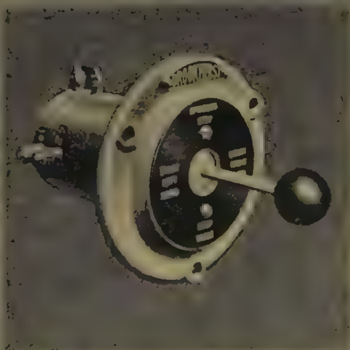
4

5

Ask to be put on the mailing list for each issue of the Brookhirst List of Stock Controlled Starters and Accessories.



6



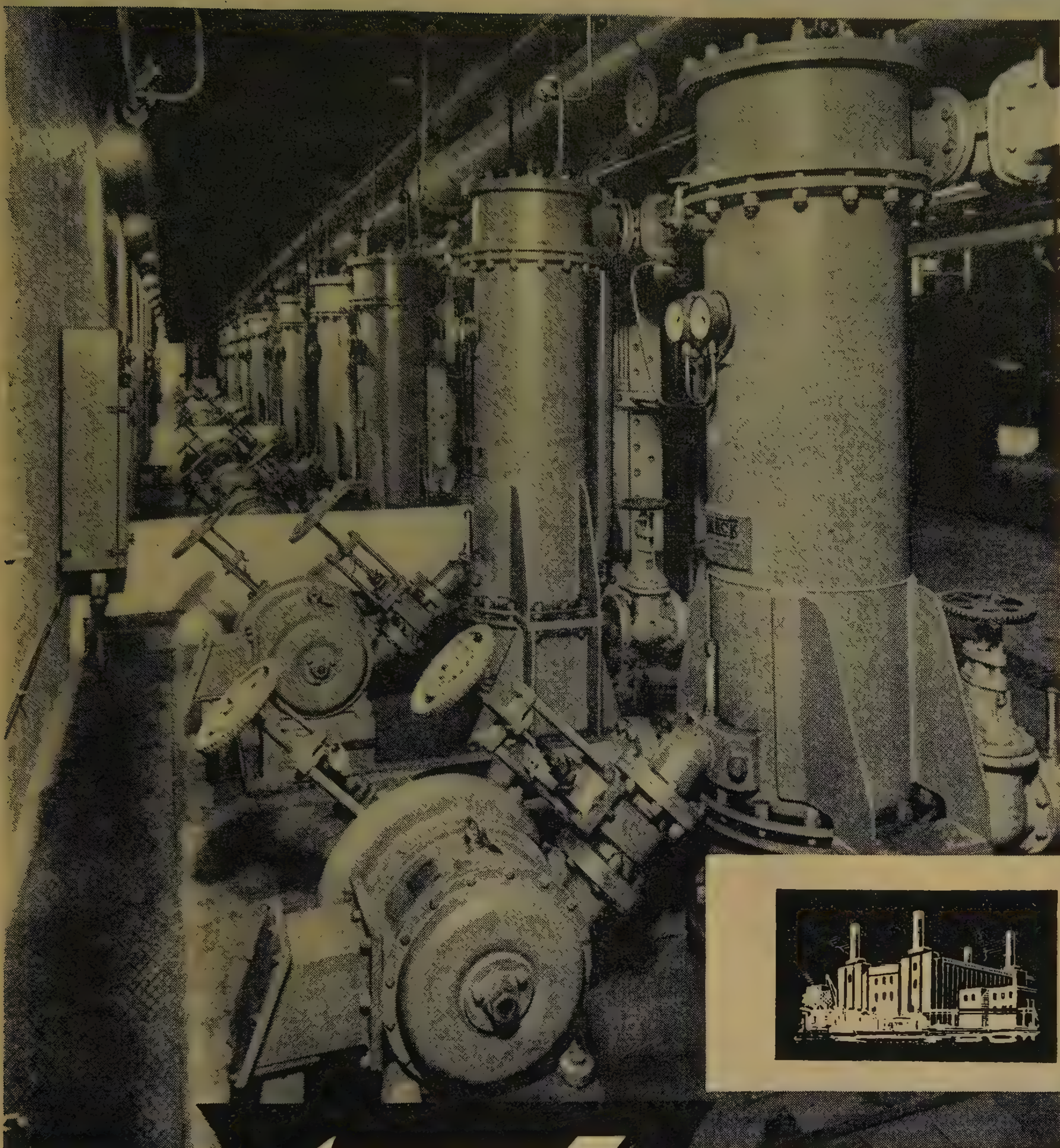
7

8

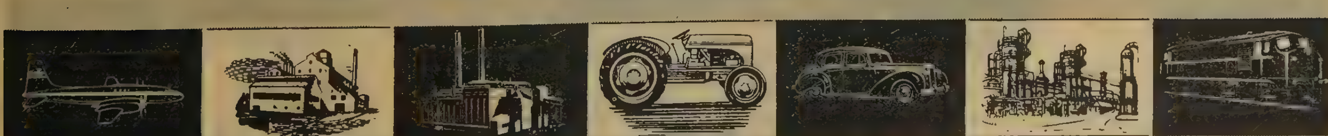
BROOKHIRST SWITCHGEAR LTD · NORTHGATE WORKS CHESTER

A METAL INDUSTRIES GROUP COMPANY

BS/43/P3738

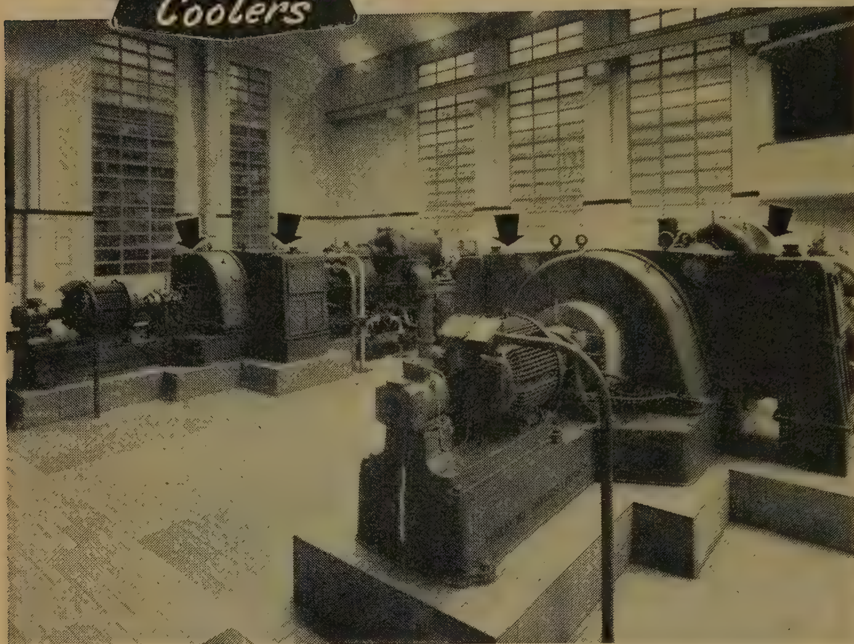


SERCK OIL COOLERS installed at a large Power Station



SPIRAL TUBE Coolers

for ALTERNATORS GENERATORS TRANSFORMERS VALVES and RECTIFIERS



Closed circuit Spiral Tube Air Coolers fitted to Alternators manufactured by the Lancashire Dynamo & Crypto Ltd., installed at the East Greenwich Power House of the S.E. Gas Board.

Over many years the company's Technicians have progressively developed special cooling equipment in conjunction with Alternator Motor and Transformer Manufacturers.

The extensive knowledge gained thereby ensures the successful solution of all cooling problems.

For most installations either water-cooled or air-cooled equipment is used, the usual Alternator or Motor Cooler is water-cooled, whilst for Transformer Cooling both water and air-cooled designs are in common use.

Each installation receives individual attention, and is designed to meet with requirements peculiar to the particular design and conditions.

Other products include Unit Heaters, Air Heaters, Diesel Engine Coolers.

THE SPIRAL TUBE & COMPONENTS CO. LTD., OSMASTON PARK ROAD, DERBY. TELEPHONE: DERBY 48761 (3 lines)

London Office and Works: Honeypot Lane, Stanmore, Middlesex. Tel: Edgware 4658/9

RECORD

GRAPHIC RECORDING INSTRUMENTS

AMMETERS
MILLIAMMETERS
MICROAMMETERS
VOLTMETERS
MILLIVOLTMETERS
WATTMETERS
FREQUENCY METERS
TACHOMETERS ETC.

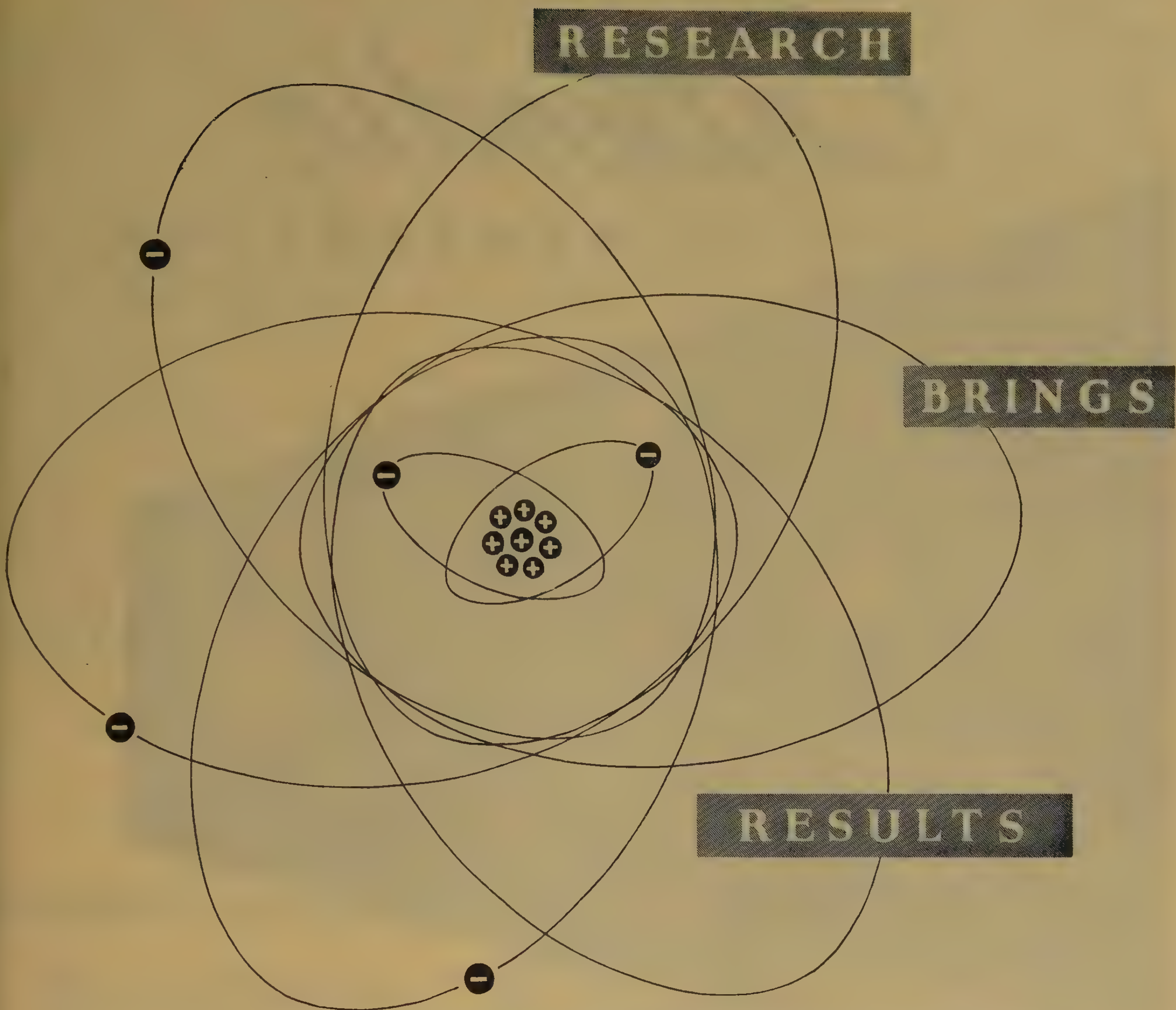
RECORD GRAPHIC RECORDING INSTRUMENTS are unable to follow current variations with the speed of the electron beam. Nevertheless, we are proud to claim that they are the fastest and most sensitive direct writing Recorders available today.

THE RECORD ELECTRICAL COMPANY LIMITED

"CIRSCALE WORKS", - BROADHEATH ALTRINCHAM - CHESHIRE

Send for folder J/a

C 4590-2



The reliability and high efficiency in design, materials and performance associated with Weir Auxiliaries for steam installations are now being applied to Weir equipment for Nuclear Power Plant.

Research, development, design and manufacture of the highest standard, maintain Weir leadership in the auxiliary field, whatever the source of energy.

We invite consultation on all questions relating to design and manufacture of Pumps, Valves, Heat Exchangers and other Auxiliaries for Nuclear Power circuits.

In the rapidly changing field of power reactor technology, the expert assistance which we can give on such equipment is essential.

Manufacturers of
POWER PLANT AUXILIARIES
for land and marine duties

G. & J. WEIR LTD.
CATHCART · GLASGOW

INDEX OF ADVERTISERS

THE PROCEEDINGS OF
THE INSTITUTION OF ELECTRICAL ENGINEERS

EDITED UNDER THE SUPERINTENDENCE OF W. K. BRASHER, C.B.E., M.A., M.I.E.E., SECRETARY

VOL. 104. PART A. No. 13. FEBRUARY 1957

Paper No. 2211
Oct. 1956

INAUGURAL ADDRESS

By Sir GORDON RADLEY, K.C.B., C.B.E., Ph.D.(Eng.), President.

(*Address delivered before* THE INSTITUTION *4th October*, 1956.)

I would, first of all, express my appreciation of the signal honour which my fellow-members have paid me in electing me as President of The Institution. The honour is one which gives me the greater pleasure because my responsibilities are no longer entirely engineering. A high tradition of service has been established by those who have filled the presidential chair and, in my turn, I will do my utmost to serve my fellow-members to the best of my ability, and to the extent that health and strength and the obligations of being a public servant permit.

The Institution

Last year Sir George Nelson reminded us of Charles William Siemens, the first President of The Institution, or of the Society of Telegraph Engineers as it was then called. To-night I recall the second President. Frank Ives Scudamore, President in 1873, was Second Secretary to the Post Office. In his Inaugural Address he said he was 'not merely thinking of the benefits which the leading engineers of the Postal Telegraph Department derived from contact in this room with the engineers of other services'. He was looking beyond, but only at that stage to the 'great body of persons' who were then engaged in the practice of telegraphy throughout the country. During the past 80 years the uses of electricity have grown from that simple start until they have become essential to every phase of contemporary existence, social, business and national defence. The Institution has adapted itself to this growth—first by change of name until it acquired its present title representative of the whole profession in 1888, second by formation of the Specialized Sections starting with the Wireless Section in 1919.

The branch of electrical engineering in which I have worked—telecommunication—has much in common with physics, whereas those members who are, for example, engaged in the building of electricity generating stations have a traditional affinity with civil and mechanical engineering, which are the classical fields. The opinion has been expressed from time to time that the organization of The Institution does not sufficiently recognize this difference in outlook. But, especially at a time such as this of rapid advance, there can be no hard and fast boundaries between the so-called light- and heavy-current technologies. Much that we do requires both. On the other hand, the present organization will not remain adequate indefinitely. The last Annual Report did well to remind us that our organization must remain flexible and The Institution must, 'as a living organism continually re-adapt itself to the requirements of the time'.

The Institution's approach to developments which lie partly outside its own domain must also be experimental. The setting up of the British Nuclear Energy Conference is an illustration. Here we have had the major professional institutions combining to create a forum in which the basic sciences and established technologies can contribute to a new advance.

Before passing to the main theme of my Address, I would add one comment on the place of the electrical engineer in society. There has been a growing realization that national survival in war and standards of living in peace alike depend on the results of scientific research, and, in consequence, the scientist has won his way into the inner councils of the nation. But in public administration or in industry there is just as great a need for the engineer as for the scientist. It is the engineer who alone can bring to the determination of policy the training and experience necessary to translate scientific ideas into machines.

The Institution, recognizing the importance of the professional electrical engineer in our national life, has had careful regard to the standards of professional qualification. These have been adjusted from time to time to take into account the more exacting nature of the service that the engineer is now expected to give, whether it be in power generation and distribution, radio communication, or the many applications of electronics. In any one of these fields there has been a significant increase in the amount of theoretical knowledge to be possessed. At the same time, rapidly changing technology has in no way diminished the need for practical training and experience. Born in the lecture theatre, the engineer is only brought up in the workshop.

Inland Telecommunication

Those of my predecessors, as Engineers-in-Chief of the Post Office who have also had the honour of being Presidents of The Institution, have mostly taken advantage of evenings such as this to describe to their fellow-members telephone development within the United Kingdom. I want to pass later to a wider theme of world telecommunication, but I must refer first to the inland system, for which the Post Office has a two-stage plan. The first stage is to install enough additional plant, chiefly local cables and exchange equipment, to satisfy the outstanding demand for telephone service. Considerable progress has been made, and

when the seven millionth telephone was connected in July the size of the system had been practically doubled since the war. The second stage comprises the progressive mechanization of the system with the introduction of new facilities.

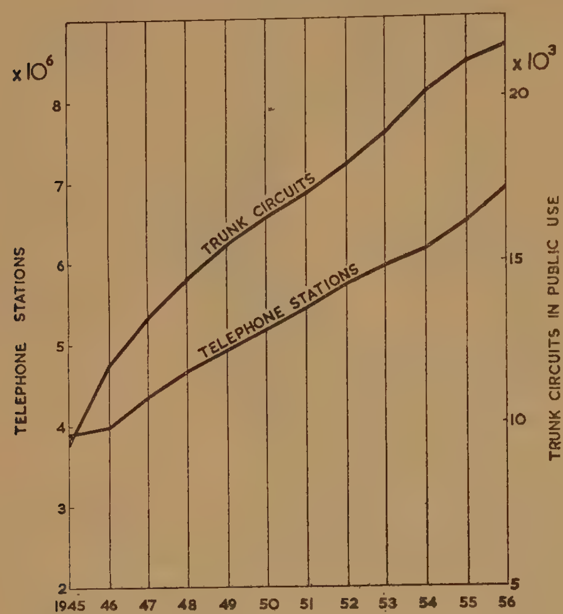


Fig. 1.—Post-war growth of the telephone system.
Figures for each year are as at 31st March.

Fig. 1 shows the post-war growth of the telephone system as a whole, and of the long-distance facilities in particular.

During the past 25 years the results of scientific research have been apparent in building up the facilities for long-distance communication. Cables transmitting 600 speech channels within a single coaxial tube have been installed between the main centres of population. The same line plant, with appropriate repeaters to transmit a slightly wider band of frequencies, is used to provide television links rented to the broadcasting authorities. With little modification it could cater for 1 000 telephone channels on each tube.

As traffic demands and opportunity offers it is proposed to reduce the spacing between repeater stations on some routes to about three miles. Modified in this way, existing cables will cater for about 1 000 telephone channels plus a 405-line television channel on each tube. Alternatively, the tube could carry 2 000 telephone channels, but it is doubtful whether the risk of losing such a large number due to a single line fault would make this arrangement attractive for general adoption. The ability to transmit telephony and television alternatively, or simultaneously, means that the repeaters must meet the requirements both of telephony in respect of low intermodulation, and of television in respect of minimum phase distortion. This is not easy. Development in any case depends on the use of valves with a performance superior to that of any at present in use in this country.

In the first Elizabethan Age, beacons signalling from hill-top to hill-top were used to transmit simple messages in emergency. The modern equivalent is the radio relay system. The facilities provided are much greater—as are the difficulties to be overcome before construction can begin. In order to build a radio station on top of a hill in rural England it is necessary to obtain the consents of no less than 25 authorities. A radio relay system has stations at intervals of between 20 and 50 miles, each station having a line of sight to its neighbours, and operates on carrier frequencies above 1 000 Mc/s. A microwave relay system of this kind is already in extensive operation in the United States, and H. Faulkner planned a comparable system extending from south to north through the United Kingdom. Essentially the system will carry up to six independent radio transmissions in each direction, and each transmission will be capable of bearing up to 10 supergroups (600 channels) of telephony, or one television channel. At terminal and intermediate stations the separate transmissions will be handled in independent amplifying equipments. This will make it convenient to lead off transmissions, as required, by spurs to cities on either side of the route. Valuable economies can, however, be achieved by the use of common aerial and waveguide systems, and by engineering the project so that spare plant, test facilities, etc., are shared.

It is a desirable feature of future development that all broadband channels should be interchangeable between cable and radio and usable for telephony or television.

Large numbers of circuits will be required on main trunk routes to cater for the anticipated growth in traffic when subscribers are enabled to dial long-distance calls, a facility which it is planned to introduce in the United Kingdom, beginning probably with calls from Bristol to London and certain other centres in 1959. Long-distance subscriber dialling should extend fairly rapidly to routes between other large cities.

In order to make nation-wide dialling by subscribers practicable it is necessary to set up a national numbering scheme; this will enable connection with the wanted telephone to be made by dialling a code to reach the area and exchange of destination, followed by the subscriber's number. The code should be independent of the point of origin of the call. A system planned with this objective must be capable, in the first place, of being grafted on to the telephone system as it stands to-day, without drastic rearrangement of plant. Because of this it is impossible to bring all local exchanges, large and small, in advance into what are known as linked numbering schemes, as in Switzerland and North America. In the second place, the national numbering system must be capable of meeting the full requirements of telephone development for many years to come. This has made the Post Office anticipate a system of 20 million subscribers connected to 8 000 exchanges.

Charging for trunk calls is now based on a ticket made out by the operator in respect of each call. This practice cannot be maintained if the full economic advantages of subscriber dialling are to be realized. Automatic message accounting equipment has been developed and is being used in North America, where long-distance calls extend to much over a thousand miles, and where various other factors differ considerably from those applicable in the United Kingdom. Alternatively, where maximum distances are much shorter, charges for long-distance calls could be derived from timed operation of the subscriber's meter with bulk billing. Electronic register translators would be suitable for the dual purpose of routing the long-distance call and of determining the meter pulsing interval appropriate to the distance.

Electronic techniques are likely to revolutionize the art of telephone switching within the foreseeable future. In America, the Bell Telephone Laboratories have announced that they will have a fully-electronic exchange in public service by 1958. Many telecommunication laboratories are pressing on with the development of systems which will render the present mechanical equipments—cross-bar as well as Strowger—obsolescent, although mechanical systems with electronic control may be used as an interim measure. So far as is known, fully electronic systems are beginning to fall into two broad types. The first uses gas diodes or some other device for interconnecting the speech circuits in a space multiplex; the second, described by T. H.

Flowers and his collaborators, uses time-division multiplex for interconnecting the speech circuits and control.

Development of electronic exchanges is at an interesting stage. The philosophy of the switching has been worked out in terms of broad functional designs. The speed with which our ideas can be realized in the form of a cheap and compact exchange depends on the production of apparatus for performing the various functions. In some cases there are alternative methods for doing what is required; for example, cathode-ray tubes with thousands of tiny capacitors deposited on the screen, assemblies of cheap mass-produced ferrite cores, and delay lines are three different forms of electronic memory for storing large amounts of information. Their future relative popularity will depend on how improvements take place.

The production cost of an electronic exchange is likely to be less than that of the corresponding mechanical equipment. Smaller and cheaper buildings will suffice to house the equipment, and incidental savings in capital expenditure on local cables may be possible if the network can be adapted to the system. Maintenance costs should be appreciably less.

World Telecommunication

The concept of a transatlantic telephone cable, having submerged repeaters at intervals to increase its traffic capacity, was first described to The Institution by Dr. Buckley in the 1942 Kelvin Lecture. Sir Stanley Angwin, in his Presidential Address the following autumn, took up the theme of transatlantic communication, and the first telephone cable system was completed last August. A general description of the design objectives for the system was given in a paper read to The Institution in November, 1954, and it is not my purpose to review the results obtained on the system this evening. That will be done in January, 1957, when papers by British and American authors, describing the cable and repeaters, will be read at a joint meeting between The Institution, the American Institute of Electrical Engineers and the Engineering Institute of Canada. The meeting will be conducted, appropriately, over the cable.

For the benefit of those members who have not followed recent developments in submarine cable technology very closely, it is well to recall that it is only the advent of the submerged repeater that has made the long submarine telephone cable possible. The attenuation of the high-frequency signals required to transmit one telephone channel, let alone a number of channels over a single conductor, is very rapid as the signals pass along the cable. In the Newfoundland–Scotland section of the new transatlantic cable the loss at the highest frequency transmitted, 164 kc/s, is about 1·6 dB per nautical mile—at this rate of attenuation the output of a 100 MW generating set could not be detected by the most sensitive galvanometer more than 150 miles away. The loss is made up by the insertion of a repeater with a gain of 65 dB—a power gain of over a million times—every 38 miles. The combination of cable and repeaters gives a system free from loss, but which depends on the continuous operation of a great deal of electronic equipment at the bottom of the ocean.

Completion of the project marks the opening of a new era in the growth of world communication. It would be appropriate, therefore, to review the usefulness to this end of long deep-water cables equipped with repeaters. The development is revolutionary in its possibilities because the capacity of this kind of cable is likely to exceed that required to replace all the existing telephone and telegraph facilities on its route, and the intention of the American Telephone and Telegraph Company to lay a replica of the transatlantic system from the United States to Hawaii, half-way across the Pacific, in 1957 means that another big step towards the development of a global network of the new kind has already been taken.

The new development in world communication must be of very considerable interest to British engineers for a variety of reasons. In the first place the United Kingdom has not only a unique tradition in the manufacture of submarine cable, but also a manufacturing capacity which is unmatched in any other country and has been greatly increased and modernized in the last few years. Next, British research on thermionic valves, and British circuit techniques are likely to exert a major influence on submerged repeater practice during the next decade. Lastly, Cable and Wireless Limited owns 150 000 miles of submarine telegraph cable, more than half the world's total mileage. Communication facilities provided by telegraph cables are limited and expensive compared with what is inherent in a modern cable with repeaters, but the old and new facilities must exist side by side, or in combination, for many years. This will create problems of use in which the Commonwealth Governments will be concerned.

In order to study the potentialities of long repeatered submarine-cable systems it is best to start from the traffic requirements, expressed in terms of the maximum frequency that must be transmitted over the cable. I have chosen 3 kc/s as the requirement for each telephone channel as a compromise between the 4 kc/s internationally standardized for circuits on land and any more economical arrangement that may be possible later using unconventional band-compression techniques which are being intensively studied. Eighteen telegraph, or telex, channels may be substituted for any one of the speech channels by the use of appropriate terminal equipment.

The relative merits of double- and single-cable systems have been much debated between British and American engineers. The use of separate cables for the two directions of transmission makes for simplicity of repeater design, and the repeaters can be accommodated in flexible housings not much larger than the cable in diameter. A single cable, transmitting in both directions, is more adaptable and, if the number of circuits required is within its capacity, will always provide the cheaper system; it is clearly advantageous when a comparatively small number of circuits is required. With a single cable, 'go' and 'return' speech channels are separated on a frequency basis and the filter elements necessary to do this in each repeater add to the complexity of the circuit and very considerably to the space required. The more commodious rigid repeater housings which are comparatively difficult to handle are therefore regarded as essential with both-way cables. Where a single both-way cable would not meet the traffic requirements, the factors just mentioned, and the frequency bandwidth which is lost in a both-way cable between the two directions of transmission, would be reasons for not using two both-way cables in preference to two one-way cables. On the other hand, there are obvious advantages in providing two independent systems where adequate alternative routing is not available.

Whichever kind of system is chosen, it is possible to work out an optimum design. As the diameter, and therefore the cost, of the cable is decreased, its attenuation increases and more repeaters are required for the transmission of the frequency bandwidth to carry the traffic.* At the present stage it is probably easier to predict the electrical performance of a combination of cable and repeaters than the future price of either. In particular, the cost of submarine cable is very largely dependent on the price of the basic raw materials, copper, polyethylene and steel. The proper cost of repeaters is still difficult to determine; but it is safe to

* For standard coaxial cable with polyethylene dielectric the attenuation varies approximately as $\sqrt{f}/d$, where f is the maximum frequency transmitted and d the diameter of the core. The working gain obtained from each repeater is limited because of restrictions on the minimum permissible input level and maximum permissible output level for satisfactory performance.

conclude that prices will remain high because of continuing high research and development charges and because of the care required in the control of manufacture and in the selection and testing of materials and components.

Fig. 2 shows the minimum capital cost of single- and double-cable schemes designed to meet various traffic requirements on a route 2 000 miles long. The traffic capacity is shown in terms of the frequency bandwidth available for each direction of transmission. The calculations on which these curves are based take into account the costs of the heavily armoured cable used at the ends of the system, where the cables are in comparatively shallow water, and also of the terminal installations. It must be emphasized, however, that the costs shown are not those of actual systems; the curves are only intended to indicate the variation and order of magnitude of costs.

Annual charges are of greater importance than first cost, and to obtain these the cost of maintenance, including occasional repairs and replacement of repeaters, has to be added to the interest and depreciation charges on the various parts of the system. Fig. 3 shows the estimated annual cost of a telephone circuit in 2 000-mile cable systems of different capacity. The assumption has been made that the system will have a life of 20 years, after which the total investment is written off; also that one repeater in every ten will have to be replaced in addition to the normal incidence of cable faults.

For the design data which have made Figs. 2 and 3 possible, I am indebted to R. J. Halsey, who has carried much of the British technical responsibility in connection with the transatlantic telephone cable.

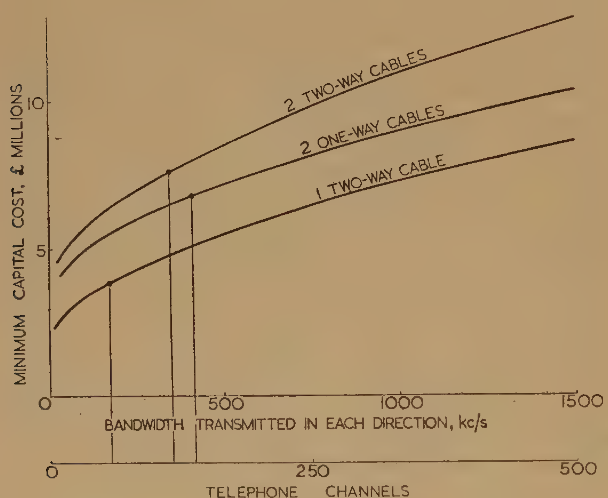


Fig. 2.—Capital costs of cable systems: 2 000 n.m.

The three ordinates indicate limits of capacity set by present construction technique.

It will be seen that the cost per circuit falls rapidly as the capacity of the system is increased. A tenfold increase, from 10 to 100 circuits, decreases the cost per circuit by a factor of about 6; another tenfold increase to 1 000 circuits would decrease the cost by a further factor of 4, or 24 times in all. It is clear, then, that the way to comparatively cheap circuits lies in using cables having a large traffic capacity. Economically, provision for all facilities, telephony, telegraphy, telex—and ultimately television—should be combined in one cable.

There are practical limitations to the kind of system we can build at present. These are set by:

(i) The maximum voltage which can be applied to the system to energize the repeaters.

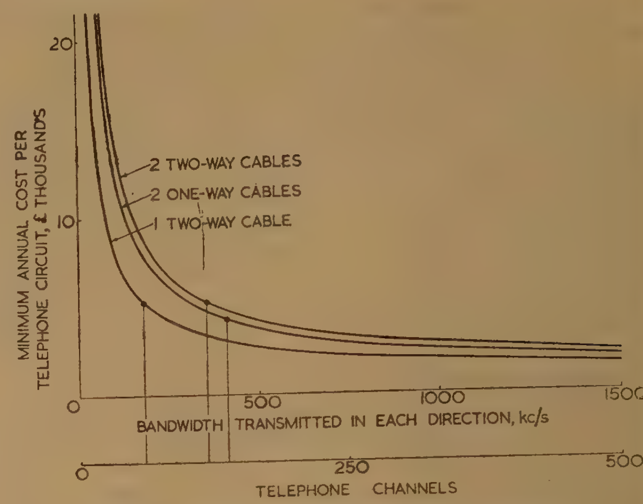


Fig. 3.—Annual costs of cable systems: 2 000 n.m.

The three ordinates indicate limits of capacity set by present construction technique.

(ii) The minimum spacing at which it is practicable to insert repeaters in the cable.

(iii) The maximum size of coaxial cable it is practicable to lay and recover for repairs.

The second and third of these limitations depend on the depth of water in which the cable is laid. All three of them present problems—in high-voltage, mechanical or marine engineering, and it will be of interest to examine the three in turn.

The 51 repeaters in each of the new transatlantic cables are energized in series by a direct current fed along the centre conductor in common with the high-frequency speech currents. This warms the valve heaters and provides the anode voltages. A total driving voltage of about 4 000 is required, the centre conductor and all the connected apparatus in the repeaters being 2 000 volts positive to the sea at one end of the cable and equally negative at the other. Repeaters could certainly be adapted for 3 000-volt working, and there is no real reason why 6 000 volts should not be possible. With valves having practicable heater designs and using low anode voltages this would permit of repeater spacings of less than 15 n.m. on a 2 000-mile cable and would cover all likely requirements, apart from television, for a long time to come.

During the last two summers, repeaters in flexible housings have been laid without incident at intervals of 38 n.m. across the Atlantic, one of them at least in a gale which would have made any cable-laying operation difficult. This kind of housing is capable of passing through the normal ship's cable gear during a continuous process of cable laying and adds very little to the hazards of cable operations. It is, however, not only inadequate for both-way repeaters but provides no room for duplication of circuit-elements or components in any repeater. Use of a duplicate amplifier, which is recent British practice, reduces the risk of failure and is particularly desirable if advantage is to be taken of new components or valves with only a short life history. It becomes therefore necessary to plan the use of rigid repeater housings generally. In shallow waters, comparatively large rigid housings have been successfully laid at intervals of 16 n.m. The methods adopted required the manual help of practically all the deck crew of the cable ship and are not suitable for operations extending over many days or in bad weather. Laying machines differing entirely from the proved and conventional drum have been suggested. Models of some have been built, and at least one has been installed on a cable ship. But there is no real experience yet as to how reliable they will be working con-

tinuously under adverse conditions at sea. Experience with rigid repeaters in deep water is very meagre. Figs. 4 and 5 illustrate the present handling of flexible and rigid repeater housings.

Fig. 4.—Flexible repeater passing through cable-laying gear.

Fig. 5.—Rigid repeater being taken past cable-laying gear.

Quite apart from any initial laying difficulties, however, replacement of any kind of repeater in mid-ocean may mean adding five or more miles to the cable length and a supplementary repeater. Until more experience has been gained, therefore, 20 to 30 n.m. should be regarded as the minimum spacing of repeaters in deep water.

Much has been learned about the laying and recovery of submarine cables during the past century, but the margin between success and failure often remains very small. The 1956 transatlantic cables are of the coaxial type required for telephony. They have a core diameter of 0·62 in and weigh about 3 tons per mile in air. They were laid without difficulty at 2400 fathoms. The same type of cable will be used next year in the Pacific, where the depth will approach 3000 fathoms (3 miles). With fair weather conditions the recovery tension from this depth is about 70% of the breaking strength of the cable and may approach the maximum permissible load on existing cable gear. Movement of the ship in bad weather will rapidly increase these forces. Cable has to be recoverable if repeaters are to be replaced, and an operation started in fair weather may have to be completed in foul. Given suitable gear, heavier cable could be used in deep water, but, with existing gear, cable with 0·62 in core should be regarded as the largest for planning purposes.

It is well known that in laying conventional cable, and to much greater extent in its recovery, stored turns in the armouring wires constitute a major hazard which is certainly not reduced when repeaters are present. Research has been undertaken on a form of structure with high-tensile-steel core which is torsionally balanced. The cable has other attractions in respect of weight and cost.

The limits set by 20-mile repeater spacing and 0·62in diameter cable are shown in Figs. 2 and 3. Because of the separate limits, achievement of maximum traffic capacity may require departure from the cheapest design, but in most cases this does not greatly increase the cost.

In the present state of the art, transistor amplifiers would compare unfavourably with valve amplifiers in respect of power-handling capacity and noise level and would be only marginally suitable in other respects. The art is, however, a progressive one, and when, as is likely, transistors of improved performance and proven reliability become available they will increase the prospects of building long cables with sufficient frequency bandwidth for the transmission of television.

The impetus given to the growth of communication between Western Europe and North America by the 1956 cable may well call for the laying of a second cable across the North Atlantic at no distant date of the greatest capacity technically possible. Eighty circuits in a single cable, or 200 in a twin-cable system, would be an objective only just outside the present limits of repeater spacing and cable diameter. If reasonably loaded with traffic at present call rates, either system would be profitable. The advances that are taking place will make still larger systems possible in a few years' time.

On other world routes the prospects are different. From a comparison of populations, circuit requirements to Australia and New Zealand are probably not more than between 5 and 10% of those to North America. Twenty-four circuits provided over a single-cable system 12000 miles long would require about 550 repeaters with an even higher standard of fault immunity than that postulated earlier. The annual charges on each circuit would be reduced if circuits were provided for part of the way in larger-capacity cables. With costs as high as they would be, cable clearly cannot be competitive on cost with radio for the provision of small groups of circuits for very long distances. Except for the use of relay stations on some radio routes, the cost of terminal transmitters and receivers is about the same for all, and this has set a pattern of uniform charges to most destinations beyond Europe.

Much has been done to improve the reliability of long-distance radio circuits, and techniques have been developed whereby more channels can be accommodated in the high-frequency band (3–30 Mc/s), which has generally been used for such circuits. The limit to the number of long-distance circuits that can be used in this band makes it certain, however, that it alone cannot

satisfy the growing need for world communication. Neither has it been possible to achieve complete reliability. Despite the improvements, it does seem clear that the propagation of high-frequency radio waves is such that continuous communication cannot be realized over such difficult routes as the North Atlantic, or to the Antipodes.

Within the past few years considerable development has also been carried out on radio propagation using 'scatter' techniques, whereby weak but consistent signals can be received well beyond the horizon. Experience suggests that links relying on forward scatter from the ionosphere or the troposphere may be more reliable than those provided by more conventional means. Unfortunately, very high transmitter powers have to be used, and highly directive, and therefore very extensive, aerial arrays are required at both ends.

Tropospheric scattering of ultra-high frequencies can be used to provide a broad-band path suitable for the transmission of television. The range is at present limited to around 200 miles, but it seems clear that successions of 'scatter' links in tandem may contribute to the growth of international communication. Apart from the possible transmission of television, however, such methods do not appear competitive with the more conventional high-frequency point-to-point radio or cable on long, world routes.

The challenge to the communication engineer is to move towards the provision of cable facilities on the main world trunk routes on a scale which has hitherto been regarded appropriate only on land. He has increasing confidence in the use of electronic equipment in quantity at inaccessible points under the ocean. What is required is a means for laying in deep water the rigid housings for this equipment without all the hazards which attend such operations at present. Development of some form of mechanical gear for doing this as part of a continuous cable-laying operation is the immediate task.

A repeatered cable from the United Kingdom to Gibraltar would appear to be a useful first step in building up communication facilities on routes other than the North Atlantic. Traffic to the Iberian Peninsula alone might not justify the investment, but the cable would have potentialities for further extension—to West Africa and South America via the Azores. A technical and economic study is being made.

Conclusion

I have departed from the tradition of the last few years in that I have not mentioned in the course of this Address our great need for more engineers and technologists, or the means of training them. I have instead described a few of the things that are waiting to be done by engineers—things in which I, myself, am particularly interested. If an echo of what I have said reaches some who are still on the brink of a career and kindles in them enthusiasm for electrical engineering, or even gives an added impetus to those of us who are already embarked on its practice, I shall be satisfied. The profession represented by this great Institution can do much to serve the Nation, the Commonwealth and the world at large.

Abstract No. 2269
Feb. 1957

SUPPLY SECTION: CHAIRMAN'S ADDRESS

By P. J. RYLE, B.Sc.(Eng.), Member.

'ENGINEERING EFFICIENCY, ECONOMICS AND EXPEDIENCY'

(ABSTRACT *of Address delivered* 24*th October*, 1956.)

The alliteration of the title is fortuitous, but the three nouns are, as it happens, those which best express three broad aspects which the engineer, consciously or otherwise, must consider whenever design and planning are the subjects of his endeavour. Usually the engineer is too busy or too experienced to worry himself unduly about these three divisions, and, in fact, they so frequently and so widely overlap each other in practice that to sit back and try to fix the boundary lines between them is an exercise likely to be more philosophic than fruitful. However, for an address such as this, I am assuming it is permissible to adopt a slightly Stevensonian attitude and to explore hopefully certain side tracks, rather than to aim at arriving at any definite terminus.

It is first necessary to adopt some approximate and rather imprecise definitions, or perhaps I should say descriptive classifications; sometimes these are permitted to have rather broader connotations than are normally used by the engineering purist.

Efficiency is the degree of success with which a piece of apparatus, a structure or a whole scheme physically performs, and continues to perform, its designed function; maximum efficiency does not by any means necessarily imply minimum cost.

Economics means the study or statement of principles, the full application of which should lead to minimum overall cost, in general comprising jointly both capital and running costs.

Expediency is taken to cover a very large field of considerations, at first sight more or less extraneous to the project, many of which may nevertheless have a great bearing on choice and design. A representative but far from exhaustive list of such considerations, in no particularly logical order, would include climate, topography, geology and transport facilities, short-term and long-term finance and planning, statutory and local regulations, accepted codes of practice, availability of suitable materials and of standardized components or shapes, dimensional limitations, use of existing stocks, co-ordination with existing or projected schemes, amenities and aesthetics, traditions and prejudices, and last but very far from least, compromise and ordinary common sense.

In the very wide field broadly covered by the term 'civil engineering', with which of course this Section has little direct concern, the concepts of efficiency, economics and expediency often overlap to such an extent that their boundaries are quite indeterminate or even non-existent. What, for example, is the efficiency of a railway line in level country from A to B? It is impossible to state in numerical terms, but it is presumably a maximum when the line is dead straight, since the railway's function of conveying traffic is then performed in minimum time and with minimum gross maintenance costs on the trains and the line itself. However, in hilly country a certain maximum permissible gradient must not be exceeded, which forces the adoption of a route nearly following the contour lines. Expediency therefore takes charge and demands a long route, but surrenders to economics when the latter clearly indicates that a cutting or, ultimately, a tunnel will be justified.

In the purely electrical world a simple example is one of the most self-contained and self-sufficient pieces of electrical apparatus—the transformer. Without too much simplification this may be regarded as a box with two sets of terminals, electrical power in one form being put in at one set, and taken out in another form at the other. The efficiency, in the ordinary restricted engineering sense, is of course the ratio of the power taken out to that put in, and, for a large transformer, is in the general region of 99%. Obviously little improvement in efficiency is conceivable, and unless one could make available insulating materials and core steels capable of running at much higher temperatures than those now used, which would permit higher overall temperatures and therefore smaller and more efficient transformers, the only imaginable change would be silver instead of copper windings. Substitution of silver for copper would only slightly improve efficiency (say from 99% to 99·1%) and slightly decrease running costs, but the increased capital cost would be such as to make the change uneconomic. Roughly speaking, therefore, we have gone as far as we can along the lines of efficiency and economics, but the expediency aspects may sometimes be quite important, especially in the field of dimensional limitations. For the larger sizes, the height and width may have to be restricted in order that the transformer, even on a special truck, can pass through the railway loading gauge; in different parts of the world, this may be either less or more restrictive than in Great Britain. For some foreign jobs, weight may be a limiting factor. Unloading from ship at some remote port may be entirely dependent on a single existing local crane of known poor capacity; again, the rail or road route to the final site may include well-defined bridges of very ill-defined strength. For the comparatively small transformers used towards the working face in mines, weight and length may not be very important, but height and possibly width may be rigidly limited by the dimensions of the underground ways through which the transformer may have to be moved. All such dimensional restrictions may result in designs slightly less favourable to efficiency and economics than those which the designer would arrive at if given a perfectly free hand. Large transformers naturally often tend to be sited in densely populated areas, and the position nowadays sometimes arises in which the ideal transformer appears to be not necessarily that of maximum efficiency or of minimum overall cost, but simply that which makes the minimum noise!

A few words on the very broad subject of standardization are now not out of place. One often uses the terms 'pure mathematics' and 'pure science', meaning those branches of the subjects which are not primarily concerned with application, although they necessarily impinge upon and influence the corresponding applied sciences. In some ways, standardization may be regarded as a pure form of expediency. The fruits of standardization are, of course, obvious and need not be listed here, but fundamentally, when new standards are first initiated it is rarely important exactly *what* is standardized as long as *something* is. At the back of all dimensional standardization lie the units of measurement, which are themselves practically all arbitrary. In fact the only units of any sort which have not been arbitrarily

Mr. Ryle is with Merz and McLellan.

fixed by man would seem to be the standard day and the standard year, decided for us by the angular velocity of the earth and the time of its circuit round the sun; to these one might possibly add the mathematical non-dimensional unit of angle, the radian, which is, however, arithmetically awkward and little favoured by the practical engineer. Fortunately the whole civilized world has agreed on time subdivision into hours, minutes and seconds; equally fortunately the early electrical scientists and engineers saw to it, in time, that only one practical system of electrical and magnetic units should be allowed to perpetuate itself. The world is not so blessed in its retention of two distinct systems of units of mass, length and temperature, the English and the metric systems.

Material dimensional standardization affords many examples supporting the thesis that as long as something is standardized it does not much matter what. For instance, wires of consecutive sizes according to the Imperial Standard Wire Gauge, in descending order, bear diameter ratios of approximately 0·9. It would be very difficult to say whether wire users would be any better or worse served if the ratio had been fixed at a slightly smaller figure, involving fewer standard wires with larger steps between, or at a larger figure with more wires but finer steps. This is borne out by the fact that other countries have arrived at slightly different ratios and, of course, at standard diameters which are all different. Among the British Standard 3-phase transformer sizes occur the consecutive ratings of 10, 15, 20, 25, 30, 45 and 60 MVA, the ratios between consecutive sizes jumping about somewhat arbitrarily between 1·2 and 1·5. It might have been more logical to adopt a constant ratio of about 1·35, but this would have made the consecutive ratings 10, 13·5, 18·2, 24·5, 33, 44·5 and 60 MVA, most of which would have been arithmetically distasteful. Rounded-off figures are therefore adopted as expedient in this case as, in fact, in most ranges of standardized dimensions.

It is now appropriate to retract, or rather to qualify, the thesis that it does not matter exactly what is standardized. The qualification is, of course, that the thesis would only be entirely valid if the whole world accepted the same standards. Owing chiefly to the existence of two different main metrical systems, world standardization of dimensions of innumerable everyday components is unfortunately unattainable and likely to remain so.

A quantity of fundamental import to the electrical engineer, one which has the dimension of the reciprocal of time, is that of power frequency. It is questionable whether a hypothetical omniscient engineer, arriving on the earth from outer space, could unhesitatingly say whether the Commonwealth and Continental 50 c/s, or the American 60 c/s, was the nearest to the ideal frequency. Higher frequency in general means cheaper rotating machinery and transformers, whereas transmission considerations favour lower frequency with corresponding lower reactances, easier voltage regulation and greater transmission stability. Anyhow, the expedient round figures of 50 and 60 are likely to persist in their respective regions, and one can only regret their inequality.

It is now proposed to examine some aspects of efficiency, economics and expediency in relation to the generation and transmission of power. Parts of this examination may be found to be discursive rather than detailed, but elsewhere the particular may be given emphasis over the general; sometimes it is rewarding to have a good look at the trees and to ignore the impressiveness of the wood.

The efficiency of a steam power station is the ratio of the electrical power produced to the heat power available from the fuel, and, owing to basic thermodynamic considerations coupled with the temperature limitations of materials available to-day, it is unlikely to surpass about 45%. Noteworthy improvements in efficiency would be conceivable only if temperatures and pressures far higher than those reached to-day were used, but such temperatures and pressures presuppose the development of so far unknown, and probably very costly, materials. The general position is that appreciable increase in efficiency implies quite disproportionate and therefore uneconomic increase in capital cost.

The efficiency of large hydro-electric generators themselves is of the order of 90%. However, the true overall efficiency of a water-power station, which can be visualized as the ratio of the electrical power produced to the potential energy or, strictly, potential power in the water above the dam, is less, on account of hydraulic losses in the tunnels, aqueducts, pipes, racks, valves, etc., between the upper water and the machines. There is clearly little scope for increasing the efficiency of the machines themselves, and some slight reduction in the hydraulic losses mentioned could be achieved only by such extreme measures, for example, as meticulous streamlining, smoothing and even polishing of the surfaces of all water passages. Such high finish could in any case only be considered effective if it were continuously maintained against the effects of silting, erosion, corrosion, weed growth and so on. Here again the very high capital and running costs debitable to the fractional efficiency improvement would be quite uneconomic.

It may be remarked here that the actual internal economics of a water-power station or system of stations may sometimes be less important than, and subsidiary to, some wider, possibly national sphere of economics. For example, in Great Britain every kilowatt-hour of electricity generated by water power, whether it happens to be very economically produced or not, may be regarded as saving another lump of our wasting coal assets. Again, the very expeditious short-time availability of water power at times of national peak load may go far towards averting power cuts or load-shedding or may help to defer the need for installing further steam sets elsewhere which would otherwise be required for peak reserve.

The siting of steam power stations, especially in a populous and much developed country like Great Britain, is a problem of ever-increasing difficulty. Ideally, of course, a power station of any sort should be located somewhere near the centre of the load it is designed to supply. However, the load transfer capacity and flexibility of high-voltage transmission systems are such that considerable departures from this ideal can be economically justified.

The primary considerations which the engineer, if given a free hand, would at once have in mind in investigating a new steam power station site are in the directions of availability of cooling-water facilities, rail, road or water access for construction and maintenance, fuel delivery by rail or water, sizes and shapes of areas required for fuel storage and for future station extensions, methods of ash disposal, and foundation conditions. Broadly speaking, the primary considerations are concerned with what the engineer wants, whilst what may be called secondary considerations are focused on the things that other people do not want. Nowadays, the so-called secondary considerations often rival the primary ones in importance. These secondary considerations embrace the possibilities of objections from local councils, military and air authorities, farming, sporting and seaside interests, the National Trust, the Society for the Preservation of Rural England, aesthetic, architectural and archaeological busybodies, and last but not least the common man and woman with their pardonable distaste for smoke, grit, cooling tower spill-over, noise or other undesirable waste-products. Combinations of any or all of such interests may result in the need for public inquiries and possibly parliamentary action, with all the costly delays consequent thereto.

The siting of a water-power station naturally raises problems rather different from those which concern steam stations. First of all, of course, it has to be situated where nature, assisted or impeded by man, provides a reliable supply of water with adequate potential energy; in other words, it must be more or less on a river or between a catchment area and a low-level discharge point. Since the general area of possible water power is often quite remote from centres of load, transmission distances may be long, and overall economics may then decide whether or not the development should proceed at all. If proceeded with, questions of fuel supply and ash disposal do not arise, and foundation conditions are usually good. On the other hand, the flooded areas caused by the raising of the water level behind the dam or dams may mean the abandoning of existing habitations or valuable land, diversions of existing roads or railways, and compensation for all such disturbances.

Objections on the score of smoke, grit, etc., will of course be absent, but strong objections on account of amenities are often raised. Such objections frequently die down completely when the station is finished; sometimes the scenery is indubitably improved and the area may even be advertised to attract sightseers. One of the most important non-engineering requirements, of course, is that there must be minimum disturbance to the pursuits and peregrinations of fish, or, far more serious, of fishermen!

Let us now turn to the subject of main transmission. For a direct-current line it is easy to show that the true electrical efficiency is a maximum at no load, which is not very inspiring. For alternating current, things are somewhat different since, even at no load, there are losses due to the charging current. Maximum efficiency, for a major line of normally correlated load capacity and length, occurs in the general region between about 5% and 20% of full load, depending largely on the line length, and may be of the general order of, say, 97–99%. At full load the efficiency is generally in the region of 90–97%. For absolute maximum efficiency an a.c. line should not only run at no load but should also be of zero length—a somewhat sobering thought! Actually, efficiency in this sense has very rarely to be considered; true economy is reached when the sum of the total annual cost of the line plus the annual cost of the losses is a minimum. The classic Kelvin's law does not, however, directly apply, since the cost of a line of given voltage, general construction, etc., is a function of the conductor size but is by no means directly proportional thereto. In any case, the application of even some modified Kelvin's law is rarely feasible except for isolated direct A to B transmission at a fairly well-defined level of power. For a much interconnected system, the average loads to be carried by any one section are largely unpredictable and it becomes expedient to decide on a standard voltage and to adopt as far as possible a standard conductor size, both being designed best to cater for the immediate and foreseeable future loading conditions and for later developments of the network.

In some ways overhead transmission lines are in a class apart from most other electrical apparatus in that they are exposed to effects almost entirely beyond man's control. These include lightning, snow and ice, gales and wind-borne objects, fog and dirt deposits on insulators, misdirected aircraft, floods and mining subsidences. It is therefore justifiable to stretch the term 'efficiency' to embrace the overall degree of success with which the line performs its function. The perfectly efficient line would never suffer any failures or experience any faults. Thus, for example, it would be designed to withstand the highly improbable but nevertheless possible condition of, say, a foot of ice on the conductors; again, quite regardless of its working voltage, it would be provided with something like 3000 kV (impulse) insulation in order to be lightning-proof. The common-sense answer is, of course, that the cost would then be quite excessive, but this immediately raises another question, 'Excessive in relation to what?' We can only honestly reply, 'Excessive in comparison with the cost of a line in accordance with sound modern practice' or some such evasive platitude. It is really incontrovertible that most of our line design levels are nothing more than expedient compromises, expedient in that they give standards of average service which have simply come to be traditionally accepted as fair enough. The true criterion of optimum design is that the total annual cost of the line, plus the annual cost of losses, plus the annual cost of outages should be a minimum. Unfortunately, the cost of an outage is a most elusive and largely incalculable quantity. Depending on the general system layout, an outage may or may not mean a failure of supply, which itself may be complete or restricted. Again, an outage may or may not involve a dangerous system disturbance, which may or may not affect consumers seriously. Failure of supply itself may or may not give rise to complaints from consumers, and these complaints may or may not emanate from levels high enough to imperil the prestige of the power authority or the poise of its public relations officers.

The general routing of transmission lines often involves a triangular battle between overall efficiency, economics and expediency. For instance, assume that voltage and conductor size have been fixed by initial economic study, and that two circuits are necessary for security of an important supply. Two single-circuit lines are more expensive than one double-circuit line, but the latter is subject to appreciable risk of simultaneous outage of both circuits from various causes, of which lightning is the most serious. On the other hand, the double-circuit line only requires one route instead of two, which is often important (and sometimes decisive) in more or less built-up areas, over valuable agricultural land, through forests, or along the bottoms of narrow steep-sided valleys. The double circuit line also means half the number of towers to litter the landscape, or to desecrate the duke's deer-park!

In mountainous country, except for peat bogs, very steep rocky hillsides or other areas involving unusual foundation or access difficulties, the transmission line engineer is usually commendably undeterred by topographical discouragements. Some approach to the most efficient, in other words the shortest, line can therefore at first sight be envisaged. On the other hand, the operating engineer is greatly concerned with easy and quick access to all parts of the line in case of trouble; this is especially so in districts where heavy snow may often make cross-country travel practically impossible. This aspect favours routing the line close to such roads as can be kept reasonably clear for motor traffic. Unfortunately, in mountainous country, the road is naturally winding and often tends to run along the bottom of a steep-sided valley which may accommodate a railway line, G.P.O. communication circuits and an awkwardly serpentine river as well. The choice of a line route along such a valley is therefore often very difficult, and its adoption greatly increases the line length and introduces the risk of electrical interference with the closely parallel G.P.O. lines.

The projected development of a hypothetical straightforward A to B transmission from, say, a water power station of clearly defined ultimate capacity might indicate the need for four ultimate circuits. Immediate load and transmission requirements might call for only two circuits initially, but lightning considerations might decide that the two initial circuits should be on separate tower lines. The cheapest scheme in *ultimate* capital cost would then be to erect two double-circuit tower lines with one circuit only on each, the remaining two circuits being erected later. On the other hand, the cheapest scheme in *initial* capital cost would be simply two single-circuit lines, the remaining

circuits being allocated to a future double-circuit line. This is a much simplified but typical example in which purely financial expediency may be overriding; very often the simple difficulties of raising money make initial, rather than probable ultimate, cost decisive. In our own home life, the bank balance limits us to buying the cheap carpet that we do not really like, whilst we know all the time that the more beautiful and expensive one would wear much better and be cheaper in the long run. But let us forget the carpet and reiterate a sometimes forgotten principle of planning, which is that it is expedient to leave a loophole for future modification of the plan. For example, the straightforward, 4-circuit A to B transmission visualized earlier might, in 10 years' time, clearly be undesirable or unnecessary, and the final fourth circuit might be much better directed, not to point B at all, but to a new load or interconnection point at X. The initial scheme would then best be a compromise in initial cost, and would be the erection of one single-circuit line and one half-equipped double-circuit line, on which the third A to B circuit could be erected later, leaving the disposal of the final fourth circuit entirely open.

Overhead line crossings of navigable rivers often present problems in which some or all three considerations strive with each other for predominance. There is nothing standard about a river crossing; the width of the river is decided by nature, together with not always convenient or picturesque modifications due to man's handiwork; the minimum clearance required between bottom conductor and high-water level is decided by the local river authority, not always with any obvious relation to the topmast heights of ships ever likely to come up-river; the Air Ministry may have its own ideas about the maximum height of towers permissible; and entirely local topographical considerations decide whether long approach spans or no approach spans at all can be embodied in the scheme.

Although not specially impressive in physical scale, a river crossing problem of more than usual interest was that of the River Orwell, at Ipswich. Here six 132 kV circuits were required to cross the river from Cliff Quay power station. The first investigation was that of the best division of the circuits among separate crossings. Possible symmetrical arrangements would have been six separate single-circuit crossings, three double-circuit crossings, two three-circuit crossings, or one six-circuit crossing. Taking efficiency in its broadest sense, the best scheme would have been six single-circuit crossings, since lightning or any other cause of disturbance would be extremely unlikely to affect more than one circuit out of the six at any one time. But six crossings would have been far the most costly, far the most unsightly, and in point of fact almost impossible on account of severe topographical restrictions in selection of tower positions at all. At the other extreme, a single six-circuit crossing would have been easily the cheapest in capital cost but would have meant an intolerable number of eggs in one basket; in particular, a lightning stroke to a six-circuit tower could easily mean simultaneous faults on several or even all of the circuits. The arrangement finally adopted was two three-circuit crossings, pairs of circuits subsequently continuing as ordinary double-circuit lines being everywhere split among the two crossings.

The next problem arose from the fact that, in effect, the river authorities wanted the towers tall, whilst the Air Ministry wanted them short. The river authorities demanded a minimum clearance to high water of 160 ft; no ships normally using the river required such a clearance, but there was apparently still in existence, in Finland, an old wind-jammer which used to visit the river in the old days and which might do so again. On the other hand, the Air Ministry were insistent that the overall height to the tops of the towers should not exceed 272 ft. Allowing for the height from tower top to bottom-conductor attachment point, this meant that the conductor sag in the crossing span had to be severely limited in order to comply with the minimum clearance to water. The conflicting requirements, together with considerations of tower design economics, resulted in the use of a special cadmium-copper conductor (instead of the normal Grid steel-cored aluminium). It was, even then, necessary to keep the crossing spans as short as possible, which meant siting the towers in difficult positions virtually at the water's edge, with correspondingly high special foundation costs.

In conclusion, this Address has been an attempt to analyse the engineering picture in which efficiency, economics and expediency are the three primary colours, and it may have removed some overlying dirt and varnish wherever these colours should be clearly outstanding. On the whole, however, the analysis has proved as inconclusive and unconvincing as would be the judgments of an art critic hopefully focusing a spectroscope on a Turner or a Titian.

The picture nevertheless remains; the reproduction itself has no marketable value, but there may be certain virtues in the frame.

UTILIZATION SECTION: CHAIRMAN'S ADDRESS

By H. J. GIBSON, B.Sc., Member.

'BALANCED DEVELOPMENT AND DIVERSITY OF APPLICATIONS'

(ABSTRACT *of Address delivered* 11*th October*, 1956.)

The use of electricity falls naturally into three main groups which are determined by the customary requirements and established habits of the community. These main groups are industrial, domestic and the rest, which for want of a better term is usually called commercial, but which includes farms, shops, offices, schools, public buildings, etc. This last group is the least well-defined and although the smallest is just as important as the others. Although there are wide differences of use and consumption by individual consumers, the electrical characteristics of each group as a whole are distinguished by significant and consistent features; in particular, the pattern of the demands which they make on the supply system throughout each day. A satisfactory method has not yet been devised to calculate with great accuracy the hour-by-hour demands of each of the groups of consumers, but it is possible to assess these within reasonable limits and to trace the form of the daily demand curve of each group.

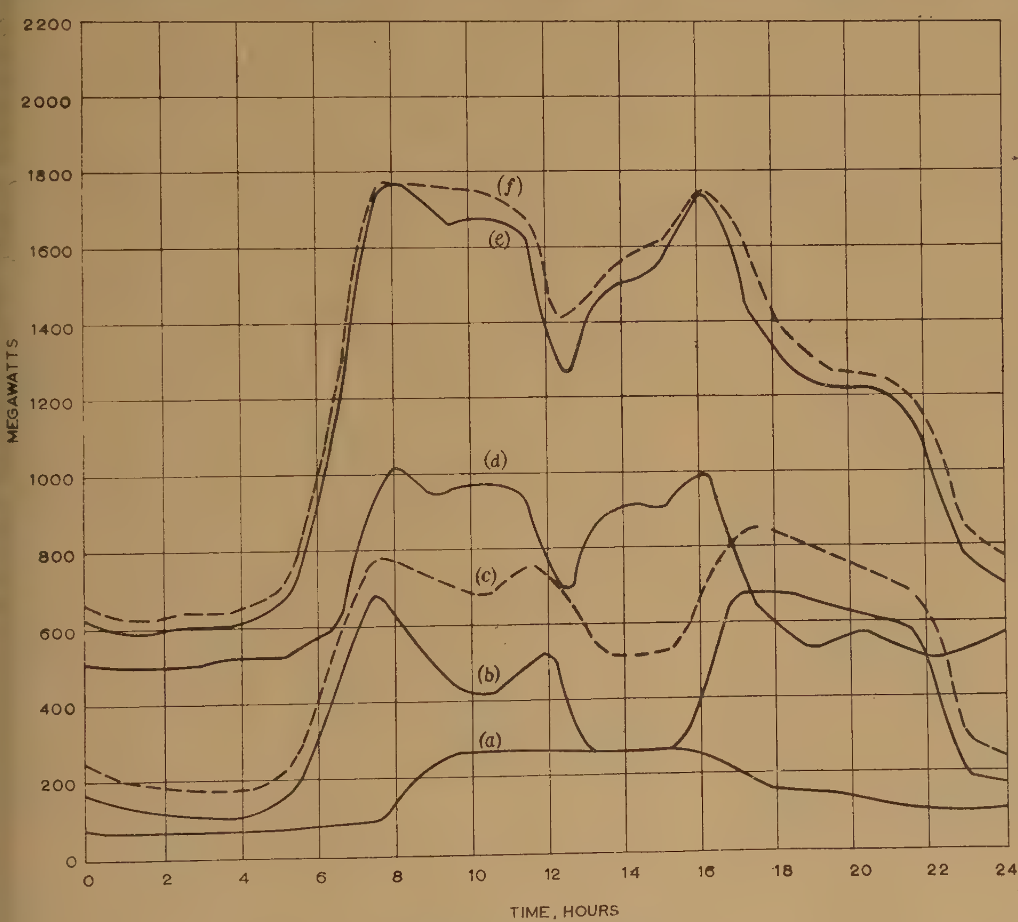


Fig. 1.—System and group load curves.
(*a*) Commercial.
(*b*) Domestic.
(*c*) Commercial and domestic.
(*d*) Industrial.
(*e*) Total daily demand curve.
(*f*) Total period maximum-demand curve.

For example, a winter daily demand curve for the domestic consumer group (Fig. 1) rises rapidly from about 5.30 a.m. reaching its highest point at about 7.30 a.m., after which it falls fairly regularly, with a slight peak at midday, until about 4 p.m., when it rises again rapidly to a point as high as, or higher than, that attained in the early morning. It is of particular significance that this high demand is maintained for the remainder of the evening. On the other hand, the curve of the demands made by commercial consumers is hump-backed, rising at about 8 a.m. and falling off again at about 4 p.m. If these two curves are superimposed the resulting graph is reasonably flat, albeit with a slight dip during the afternoon, but extending, owing to domestic consumer requirements, at a high level well into the evening.

The industrial demand curve follows a shape somewhat similar to that for the domestic group, but rises more rapidly a little later in the morning, attaining a maximum between about 8 and 9 a.m. It then falls in a somewhat irregular manner, with a substantial dip at midday, rising to a maximum again at about 5 o'clock, when it drops off rapidly to a proportionately low value for the rest of the evening. By superimposing the combined domestic and commercial curve on the industrial curve the general pattern of hour-by-hour demands on the supply system can be seen. Finally, if the maximum demands on the system for each half-hour of each weekday during the three winter months are plotted, this produces a composite curve which is similar in form to the daily load curve but flatter and with fewer and less pronounced valleys.

One significant point brought out by studying this set of curves is that, whilst each of the groups has characteristic irregularities,

Mr. Gibson is with the Midlands Electricity Board.

they are to a considerable extent complementary, and a substantial diversity of requirements between the three groups is indicated. This situation has been brought about by the extended use of electricity and its adaptation to an increasing variety of applications in factories, homes and commercial premises, and has resulted in a continually improving system load factor. It is evident that if this improvement is to be maintained the development of the three groups must continue in unison and more and different uses must be encouraged.

It is apparent from the composite curve that there are periods during the day to which existing applications might be extended or new ones introduced with benefit, and the low usage of all groups during the night invites attention and ingenuity to provide a means of using electricity during these periods in such a way as to circumvent well-established customs and habits. The wide diversity of use within each group is of equal importance, and many applications having individually low load factors can play as important a part in the general improvement as those of higher load factor.

The financial necessity of making the maximum use of capital plant demands the continual study and application of balanced and selective load development and the correct and efficient use by customers of their electrical equipment, and the intricacies of a modern rapidly growing electricity supply system provide a variety of changing problems. Properly constructed statutory tariffs and special tariffs can provide inducements to customers to improve the load factor and power factor of their loads, but the use of tariffs is circumscribed and other methods must frequently be adopted. Moreover, the significance of tariff structure is seldom understood by customers, who must be advised and guided as to the best use they can make of the electricity supplied to them. It is therefore necessary for commercial engineers of Area Boards (perhaps a more appropriate title would be 'utilization engineers') to have a wide knowledge of the various established applications of electricity and to concern themselves actively with new applications and the adaptation to electrical methods of operations and processes at present done in some other way. A number of examples follow which indicate the general direction of activities designed to achieve the maximum use of capital plant and the progressive improvement of load factor which are of equal importance to suppliers and users alike.

An application of electroluminescence which is still in the early stages of development consists of a fluorescent material deposited on some suitable medium which is activated by the passage of an electric current amounting to no more than a fraction of an ampere at low voltage. The light obtained from such a source is limited, so that at present its use is restricted to minor applications. When contrasted, however, with, say, an electric arc furnace having a capacity of 50 tons and a maximum demand of 30 000 kW, the two applications serve to indicate the wide and diverse range for which the public supply of electricity is used.

Furnaces of this type have proved to be suitable and economical for the production of lower-grade steels, and the trend to-day is for them to supersede the open-hearth process. This is due to lower capital costs and competitive running costs, together with the saving of valuable space, including that required for coal storage, the difficulty of ensuring regular supplies of coal of uniform quality, and the ability to use a higher proportion of scrap, including borings, with no reduction in the quality of the product. Arc furnaces of this size present some special technical problems due mainly to the peaky and violent fluctuations of load, and special precautions must be taken to minimize the effect of this on the distribution system.

The load factor of an individual furnace is about 35%, but the cycle of operation requires a high demand during the melting period and much lower demand during the soaking period. If the working cycles of two or more furnaces are staggered, which can be done without affecting production, the maximum demand can be kept at a reduced figure for certain periods of the day during winter specified by the supply authorities. This arrangement makes it possible for them to quote a special tariff the demand component of which is commensurately low. Thus this application provides an example where a special tariff can be designed which, with the co-operation of the consumer in operating the plant, can help to improve the supply system load factor and attract to the customer an immediate financial benefit.

Between these two extremes, of the small-current appliances requiring a fraction of a watt for quite short periods and the heavy loads requiring thousands of kilowatts almost continuously, lie the hundreds of applications of great variety in the factory, home, farm and commercial premises requiring electricity in varying quantities at different times and for different periods, thus providing by customary use the diversity which contributes so materially to the economies of a supply system.

A somewhat uncommon use of public electricity supply is for the purpose of energizing the cyclotron and synchrotron at Birmingham University. These machines reproduce at ground level some of the phenomena known to exist in cosmic radiation and enable scientists to extend their study of nuclear physics.

The synchrotron consists of a ring-shaped electromagnet made up of C-shaped laminations assembled in a circle with the gap outwards, the windings, which consist of flat copper conductors, being designed for an r.m.s. current of 4600 amp with a peak current of 12 000 amp at 1 100 volts. Protons produced by an electric discharge in hydrogen are injected into an annular vacuum tube which is located between the poles of the magnet. The protons circle the vacuum tube and are restricted to a circular path by increasing the magnetic field. Once each revolution they pass a gap between two electrodes across which a radio voltage of increasing frequency is maintained. This accelerates the protons and a controlling device ensures that the magnetic field is increased at the correct rate as the protons are accelerated. They are ejected from the annular tube by arresting the increase in the magnetic flux and the frequency of the accelerating potential, and leave at a speed approaching that of light one second after entering the annular tube. During this one second the magnetic field is built up to a maximum of 15 000 gauss in the mean gap between the poles of the magnet of 21 cm. Nine seconds is occupied in suppressing the magnetic flux so that the duty cycle is 1 in 10 sec. The power to excite the magnet is obtained from two d.c. generators operating in parallel, each driven at 500 r.p.m. by a 1 500 h.p. 11 kV 3-phase 50 c/s induction motor. A 36-ton flywheel coupled to the machines minimizes the effect on the supply mains of the rise to peak load (of the order of 8 000 kW) in one second in every ten.

The results of the study of nuclear physics made possible by these machines has contributed and is contributing in no small measure to the development of the peaceful uses of atomic power. This is of the greatest importance to this country, for it is by the exploitation of our scientific and technical skill that we can maintain our position as a leading nation. There is ample evidence that British engineers are not backward in translating scientific principles into practical application, and on the evidence of the revised programme for nuclear power stations it is obvious that our great industrialists will not be behind in extending the lead already achieved in this sphere. With the experience they gain by building atomic power stations in this country during the next few years, it is possible that they will, in the foreseeable future, be in a position to sell 'package' atomic power stations to the Commonwealth, to China and other countries where other

fuels are expensive and thus create a vast potential market for other electrical machinery and appliances. Perhaps they may even sell them to America.

In view of the operating conditions of the induction motors driving the d.c. generators supplying the synchrotron, it is not surprising that the power factor was only slightly over 0·6, and the installation serves to illustrate another important factor in supply and utilization which is of direct interest to both supplier and the user. The phenomenon of lower power factor is inherent in those electrical machines which embody magnetic circuits such as motors and welders. In most factories by far the greatest use of electricity is for motive power, and although it is possible, by the proper appreciation of the whole sequence of processes and by the right selection of motors, to design a factory system to operate at a power factor as high as 0·85, this is seldom achieved in practice. Plant, cables and switchgear of both suppliers and users must, as a result, be of greater capacity and more expensive than they need to be. To make the fullest use of capital, therefore, users should take all steps to improve the power factor of their installation by installing power-factor-correction equipment. This is so important to the Area Boards that they frame their two-part industrial tariffs to measure the maximum demand in kilovolt-amperes or alternatively to apply a penalty for power factor below a given value.

By the provision of 370 kVAr of capacitors at the 11 kV input to the motor-generators supplying the cyclotron and synchrotron at Birmingham University, the power factor was improved from 0·6 to 0·95. The cost of the power-factor-correction equipment was offset by the saving in electricity charges within two years, and in addition substantial increased capacity was made available on the internal and external cables.

Whilst motive power constitutes a major part of the industrial use of electricity, process heating in many different forms is well established and is expanding at a remarkable rate. This is because electricity has a high utilization efficiency and heat can be applied precisely and uniformly exactly where it is required, with accurate and dependable automatic temperature control in atmospheres completely free from deleterious fumes or gases. In addition, valuable space is saved, wastage is practically eliminated and labour costs are reduced.

Perhaps one of the most outstanding examples which demonstrates all of these advantages is the recently introduced new type of electrically fired intermittent pottery kiln. Although the traditional coal-fired bottle kilns, of which there are still over 700 in operation, were intermittent in character, very little attention was given to an electrically fired intermittent kiln until 6 or 7 years ago, when the Midlands Electricity Board in co-operation with a number of leading potters developed a successful design. This proved to have many advantages over the continuous kilns for certain classes of products.

The development of electrically fired pottery kilns for the higher-temperature processes was previously handicapped by the instability and heat-retaining properties of the fire-brick used, which contributed to failure of heating elements. By the use of high-grade insulating fire-bricks with low heat-storage capacity and an ingenious arrangement of elements of special alloy supplied at a low voltage which minimizes the potential between adjacent elements, these intermittent kilns are capable of operating at temperatures up to 1 300° C.

The kilns are constructed with the walls of the chambers supported by a steel framework; grooved fire-brick supports the heating elements, which are led through wall tubes to the outside. Part of the heating elements are provided in the truck door, which is built to seal the joint effectively when the truck is in position. They are arranged in pairs side by side, the firing chamber being 9 ft long by 2 ft wide by 3 ft 6 in high. The trucks carrying the ware are mounted on a trolley which can conveniently be rolled into either kiln on rails provided.

In all these kilns the elements are supplied at 90 volts through a single-phase transformer for each pair of kilns, twin kilns being operated in convenient banks to balance the load. Each kiln is rated at 72 kW, including door and truck base, which is equivalent to 6 watts per square inch of chamber area. The electrical circuits of each pair of kilns are interlocked to ensure that only the operating kiln is switched on, and firing is regulated by a simple electronic controller preset to the required temperature, danger of overfiring being prevented by an automatic cut-off device.

These intermittent kilns are used for decorating, glost and biscuit firing of china and pottery at temperatures ranging from 650° C to 1 200° C. The trucks for china and earthenware will take 60–70 pieces each, and by the proper combination of type and position of ware, a double kiln can be operated on a 24-hour cycle, permitting each truck to be loaded every 48 hours, the twin kilns working seven days a week. The load factor attained by operating kilns in this manner is about 90%. Because industrial tariffs embody a reducing unit charge related to load factor, the running cost is low and on an average about 55% of the coal costs for the older type of kilns.

An added advantage of these kilns is that they contribute to the improvement of power factor of the installation as a whole. This applies, of course, to all resistance ovens and furnaces for whatever purpose they are used, and should always be taken into account when comparing electric furnaces with other methods.

It is notable that no saggars are required with this type of kiln for china and earthenware, and repairs and maintenance have proved to be one-half the cost of coal ovens.

From these horizontal kilns a leading manufacturer has developed a vertical kiln with the heating elements contained in a 'top hat', which covers the charge to be fired. A set of six kilns of this type (two more are shortly to be installed) are used for firing high-grade china. These vertical kilns are arranged to work in pairs in the same way as the horizontal kilns.

The main advantage of the 'top hat' kiln is that the ware is not subject to vibration as it is in the horizontal kilns when the trucks are being pushed in and out and along the transverse. Also, because of the special construction, it is not possible for draughts to cause cold spots in the setting as sometimes occurs through the door seals of the horizontal kiln. The pottery manufacturer who is using these kilns states, 'In our particular case electricity is cheaper than coal, and though it might be slightly more expensive than the gas-fired tunnel ovens per cubic foot, the savings in labour and other costs more than compensate for the difference'. Thus the electrically heated intermittent kiln provides an example of the adaptation to an electrical method of a process previously done in another way.

Problems sometimes arise which are capable of solution by applying to them the technique used in other processes or sometimes by a machine with which the individual customer is unfamiliar. In other cases, however, a solution has to be sought by experiment. Most of these do not involve much capital equipment, and manufacturers therefore have no direct incentive to interest themselves.

An interesting example of this type is the electric drying of gypsum plaster moulds for the manufacture of pressure-cast match plates. This process makes it possible to produce an accurate initial casting with such a fine finish that it can be used as a pattern, and the method is particularly suitable for relatively short runs of special items. From each 1 lb of plaster 1¼ lb of water have to be evaporated, and this presents a serious problem. Drying in the conventional recirculating air stove occupies about 10 hours for every inch thickness of plaster, and even so considerable wastage occurs owing to irregular drying, which causes

the moulds to crack. Moreover the long periods during which drying ovens are occupied by the plaster moulds slows down the drying of sand moulds resulting in reduced production. The capital required for additional oven space would render the process uneconomic.

The method, however, has so many advantages that foundrymen were anxious to explore every means of drying, and a suggestion was made that this should be done electrically. Following a number of initial experiments, it was decided that drying by means of an expendable current-carrying wire, cast into the plaster, offered the most promise. It was necessary for the wire to be cheap and readily obtainable through normal trade channels, and for the 'cages' to be easily made and inserted by semi-skilled labour. Tests were made with plaster moulds about 6 in cube, and current was supplied to the embedded wire at between 4 and 12 volts. After several of the 6 in cubes had been successfully dried, experiments were extended to a light mould of standard size used in practice. The maximum loading during the drying is 1 800 watts, and the period for complete drying is determined by the time taken for the internal temperature to rise to a predetermined maximum which previous experiments had shown to be 200° C; this takes substantially less time than the 60 hours in an orthodox recirculating air stove.

In later experiments, reusable metal tape was used as a heating element. It was found possible to keep the formation of the cage quite simple by clipping small slips of metal tape thereto which projected into depressions in the pattern, thus conducting heat from the element to the pockets of plaster. The casting of the metal plate pattern follows the usual procedure. Metal is poured at 600° C and is forced into the mould through a pressure cylinder at 2–4 lb/in^2. Thirty to forty minutes are required for the metal to solidify and cool sufficiently before removing it from the plaster.

One of the obligations of Area Boards is to extend electricity to country areas, and although there is a large potential use of electricity on farms and in country houses, the development of the load is inevitably slow. To make the maximum use of capital expended on mains and substations, every encouragement is given to industries having some association with rural activities to establish factories remote from industrial and urban centres, and adjacent to distribution lines. The advantages to the users of doing so outweigh the disadvantages, and a typical example is a factory producing fruit extracts, notably blackcurrant syrup, at Coleford in the Forest of Dean.

The factory is founded on scientific research and to almost a unique degree purity and quality control are exercised throughout the operations. There is collaboration between the laboratory staffs and hospitals and other medical authorities in a number of controlled clinical tests, and in addition there is continuous activity in fundamental research. Contemporary colour schemes and modern fittings are the outward expression of the desire to encourage cleanliness and the right atmosphere among employees.

After gathering, the blackcurrants are mulled, subject to enzyme treatment and carbon-dioxide impregnation, and are clarified. The first removal of the sediment is achieved by vertical and horizontal vibration of the juice, after which it passes through a centrifuge. It emerges from this process still slightly cloudy, and the last trace is removed by flash pasteurization. In one minute the juice is heated to 185° C and cooled to freezing point. The treated extract is then put into cold store. This is perhaps the most impressive department in the factory. Cut out of the solid rock are two underground chambers containing a series of 5 000 gal glass-lined cylinders in which the juice is stored under pressure of 45 lb/in^2 at freezing point until it is required for syruping and bottling. The total refrigerated storage capacity is a little under 300 000 gal.

This refrigeration storage system, believed to be the largest in the country, enables the processing of the blackcurrants, which are harvested within four or five weeks, to be spread over the whole year. This, of course, has many advantages leading to economical production, not least among which is a reasonably consistent maximum demand from month to month of an average of about 280 kVA, which, with a consumption of over 1 000 000 kWh per year, results in an annual load factor of about 33%. The average cost of electricity for the year 1955 was 1·135d. per kWh.

For many years, supply engineers have been seeking ways of inducing consumers to use electricity during night hours and have had some success in the larger factories, but the modern trend is for short working hours and a five-day week. Moreover, by nature and habit human beings rest and sleep during eight hours of darkness, so that the most promising possibilities are applications which will store energy given up by electricity during the night for use during the day, and storage space-heating and water-heating immediately suggest themselves. The circumstances warrant a specially low tariff which provides inducement to consumers to accept a method which may involve them in capital costs which otherwise they would not necessarily have to incur. In fact, this is generally not the case, the capital involved usually being less than required for alternative methods.

The development of several types of insulated electrical resistance cables which can be buried in the floor to heat the structure of a building during the night offers wide possibilities for the future. Considerable experience has now been obtained with the electrical method of floor warming, an example of which is a new single-storey factory with a floor area of 25 000 ft^2. The whole of the factory, including stores and offices, is heated in this way. The steel-framed building with a pitched roof has 14 in brick cavity walls to a height of about 5 ft, with extensive single-glazed windows all round. In this particular installation a copper-sheathed mineral-insulated cable is buried direct in the concrete floor. Adjacent circuits are interleaved without crossing, in such a way that uniform heating is obtained and all heat is not lost in a particular section should one circuit be disconnected for any reason. Each circuit is controlled by a contactor and time switch which can be set to regulate its period of operation. Air thermostats fitted in suitable positions in the building limit the maximum temperature, and a master thermostat fitted outside provides an anticipatory regulation. Because of the high air temperature specified in this particular case, the floor warming is supplemented by a few self-contained thermal storage heaters, thus bringing the capacity of the whole installation up to 400 kW.

Experiments to extend the principle of floor warming to glasshouses have been going on for some time. The heating cables are embedded in the concrete walk along the centre of this experimental greenhouse and are controlled by internal and external thermostats. The technique is somewhat different from the space heating of buildings, and air humidity has to be more carefully regulated for certain crops. The results so far are surprisingly good—so much so that a large chrysanthemum grower has recently decided to equip all of his greenhouses in this way. Experiments are also being conducted on night-time soil warming with every promise of success, and here again an enterprising market gardener used the method to produce lettuces last winter.

In this very brief survey, attention has been focused on diversity, load factor and power factor, three characteristics which are of major importance to supply and utilization. A number of examples have been quoted to illustrate some aspects of selective load development to achieve the best overall results.

BRANCH, CENTRE AND SUB-CENTRE CHAIRMEN'S ADDRESSES

Abstract No. 2315
Feb. 1957

IRISH BRANCH: CHAIRMAN'S ADDRESS

By P. H. GREER, Member.

'THE MANUFACTURE OF ELECTRICAL EQUIPMENT IN IRELAND'

(ABSTRACT *of Address delivered at* DUBLIN, 18*th October*, 1956.)

A description is given of the electrical power installation in a modern heavy electrical products factory in Ireland. The factory (Fig. 1) is of medium size, having an original site area of 30 acres, now extended to double this figure. Such extension is provided to allow for all future expansion of the works.

Maximum Demand Control

Power is supplied at 10 kV and purchased on a maximum-demand tariff. The kilowatt demand is measured over a 15 min period, and any excess load can seriously influence power costs. Strict control is exercised by means of two supervisory instruments, one measuring the demand applying over each 5-minute period and supervising controlled plant, and the other over each 15-minute period. If an excessively heavy demand occurs during the last part of the 15-minute period it is dealt with by the second instrument, which shuts down not only controlled plant but also certain other items.

During November to February the Electricity Supply Board offers a special incentive for demand restriction during the period 4 p.m. to 6 p.m. The demand charge applies only during these hours. Participation is optical but has been found worth while. Arrangements are therefore made to by-pass the thermostats on thermal plant a short while before the period of restriction, so that such plant enters this period at maximum allowable temperature. They are then arranged to fly over the period without further input. Some plant, however, must have some power to maintain temperature above a critical level, and a synchronous-motor-driven controller was designed to ration the available supply period to these items during each 15 minutes.

Fig. 1.—General view of the factory.

High-Voltage Distribution

The advantages of a high-voltage distribution system have been obtained, while the disadvantage of high-cost switchgear has been largely eliminated by the use of a transformer-mounted low-priced 10 kV link box, designed especially for the purpose. An h.v. ring main is therefore employed with transformers and link boxes at the various points of load. Considerable economies in l.v. cabling result. This system deals at present with an installed load of about 3 000 kVA.

Cable Ducts

Much thought has been given to the provision of an adequate system of cable ducting throughout and around the factory. Main outdoor service ducts, factory service ducts and under-road ducts carry all services except gas, which for safety reasons has been run separately. An unusual system of final ducting was designed. This provides for a series of $2\frac{1}{2}$ in diameter holes at 36 in centres moulded in the factory floors during building, traversing them from main duct to main duct. Power, air, water, etc., may then be provided within a few inches of any machine.

Heating

In the most recent of these factory buildings, an electrical floor-heating system of our own design has been installed. This employs a heating element consisting of a robust high-tensile

Mr. Greer is with the Aberdare Electric Co., Ltd., Dublin.

wire contained loosely in a plastic tube with an overall diameter of approximately $\frac{5}{16}$ in. Being, in fact, just an electric cable on which the insulating sheath has been loosely applied, it is produced by standard means in long lengths at low cost.

With this system the cross-section of the wire may be large and in consequence robust and unlikely to fail. Two parallel ducts at up to 100 ft spacing are provided in the floor, and, should it become necessary, the wire can be pulled out and replaced without floor disturbance. Such an arrangement, we have found, offers extremely low capital expenditure and may be installed without increase in normal floor construction times.

Developments

In 1948, when operations were begun, increases in the prices of copper rendered this material uneconomical as a conductor. Steel-cored aluminium conductor then largely replaced copper in the Irish rural electrification scheme. This fortunate occurrence, though it was not recognized as such at the time, caused us to begin the manufacture of this material. Since then our interest in aluminium wire, and in aluminium generally, has steadily increased.

The factory plant for the production of s.c.a. conductor (Fig. 2) is among the most modern at present existing, and a short description may be of interest.

First, pigs of aluminium are loaded into a 10 000 lb oil-fired melting furnace. The metal is then discharged by tilting the furnace into either of two 180 kW electrically heated resistance furnaces. Here it is held at pouring temperature, quiescent, for an hour or so. The holding furnace tilts slowly to discharge the metal in a continuous stream via a small holding pot into a cavity on the rim of a rotating water-cooled casting wheel, made of copper.

A steel band runs on the rim of this wheel to form a closed mould. The wheel or mould rotates at a speed of about 3 r.p.m. By the time the metal has rotated from the casting point through about 180°, enough heat has been taken from it to cause solidification.

The continuously cast bar, already at rolling temperature, is then led from the wheel and fed into the rolling mill, whence it emerges as a continuous length of wire rod.

This rod is in its turn automatically coiled into a storage pit, from there being continuously fed to the wire-drawing plant. This plant is, in itself, unique, as the drawing operation is not interrupted for bobbin removal.

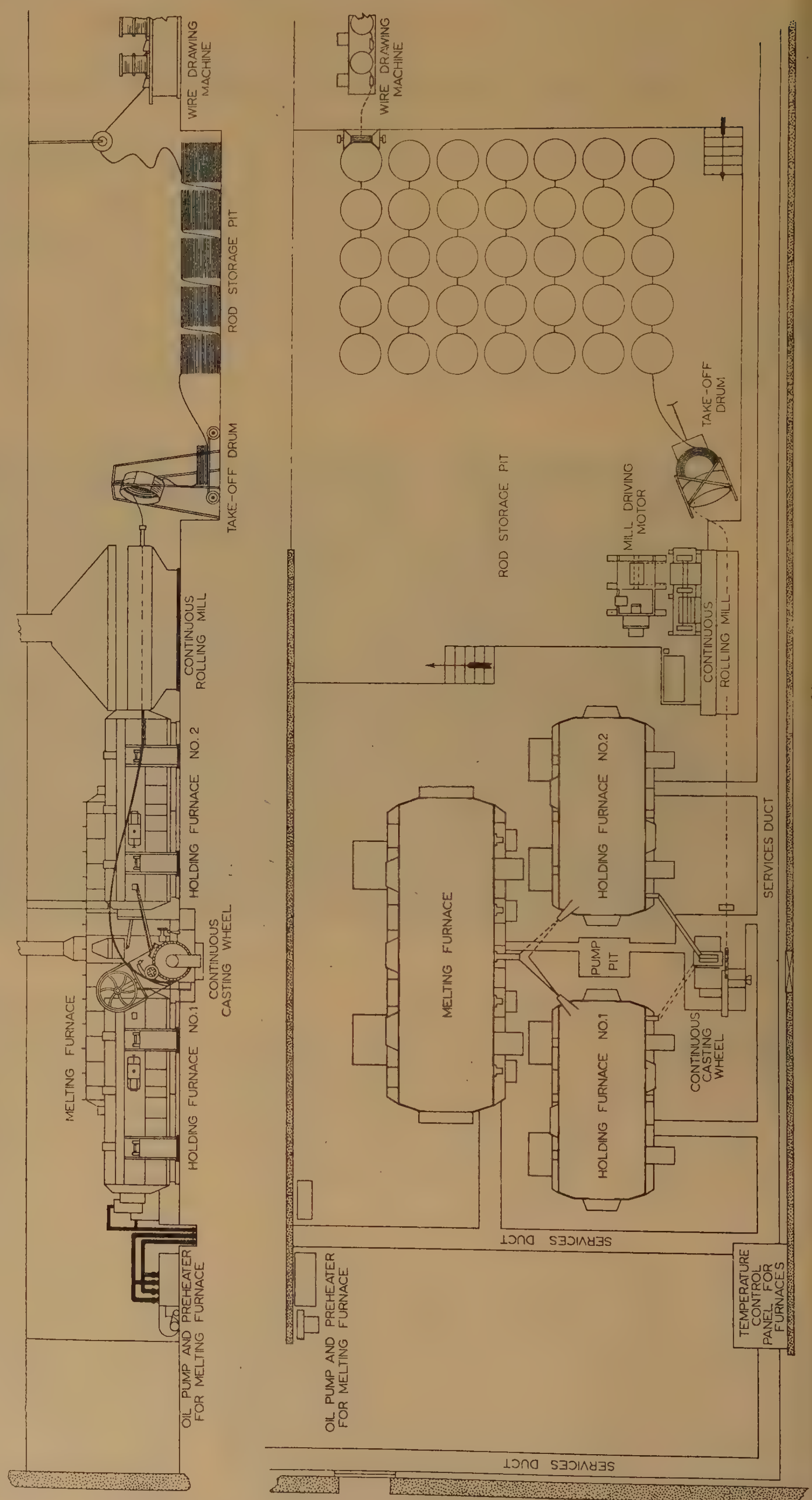


Fig. 2.—General layout for continuous production of aluminium wire.

It will be appreciated, therefore, that this complete process from ingot to wire may be run continuously, avoiding wire bar reheating and the variously disjointed operations of previous methods. Further, the endless production of wire rod means that welding is avoided, in the wire-drawing operation, so that a wire of very high quality can be produced. It is considered that this new process is likely to increase the availability of high-quality aluminium wires and render them even more competitive with copper.

A development which, however, is expected to be of greater impact is now on the horizon. This is the use of anodized aluminium wires, etc., for electrical machine windings. In this product no organic insulation is present on the conductor, the entire insulation being provided by a very thin layer of aluminium oxide built up by an anodizing process, the thickness of the layer varying between 0·000001 and 0·0004 in. This development has, of course, been discussed for many years, but it has recently become much more of a reality with the development of continuous anodizing processes. Much remains to be done before this becomes an everyday application, but progress is undoubtedly being made.

Perhaps an even more interesting development is the use of anodized aluminium strip or foil for electrical windings. This offers a very considerable saving in space, and therefore in cost. It would appear that in many cases a transformer or motor with this aluminium winding can be made no bigger than the equivalent copper machine and with a saving of weight of up to 50%.

A transformer using anodized aluminium strip (Fig. 3) has been designed and manufactured in this factory. It is of 400 kVA 3-phase 50 c/s 10 kV 394/227 volts rating, and since there are a number of problems associated with the use of such material, it is of the normal oil-filled type. The losses and size will, it is expected, compare with those of a standard copper-wound machine. Considerable promise is also shown by this material for use in dry-type transformers. Only recently have the problems associated with the use of anodized oxide-film insulated conductors, such as surface preparation and uniformity of coating, come near to being satisfactorily solved. The foil or strip conductors may be slit from a roll of aluminium foil. If these strips were anodized, however, without further processing, a microscopically ragged edge would cause points of premature breakdown on test at low voltages. Before anodizing, it is therefore necessary to provide a half-round section at each edge so that a uniform film thickness of anodic coating is obtained all the way round. Results of breakdown tests on treated and untreated edges are shown in Fig. 4.

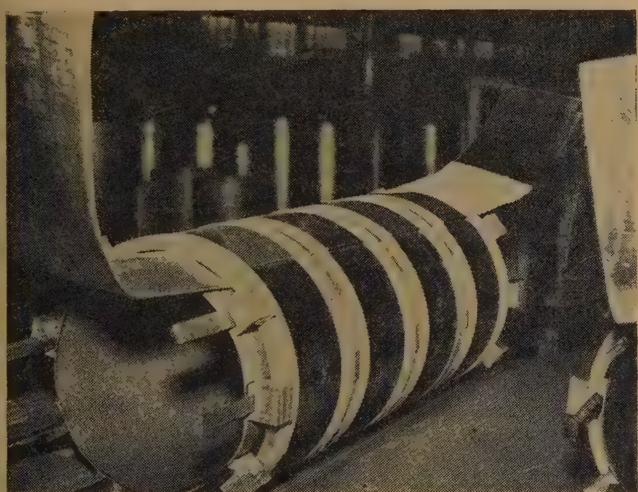


Fig. 3.—Anodized-aluminium-foil transformer coil.

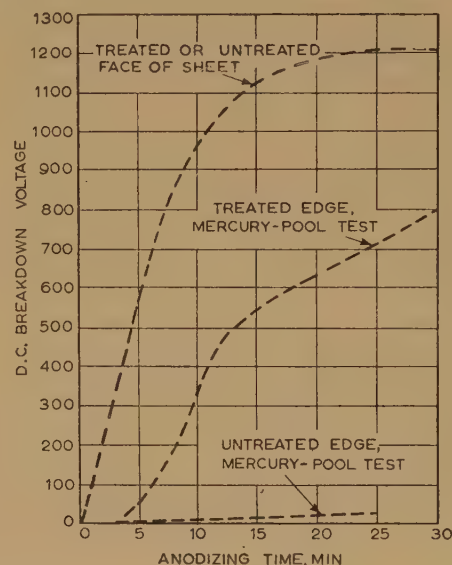


Fig. 4.—Insulation efficiency of anodized aluminium foil.

It will be noted from the top graph that the insulation efficiency increases rapidly up to 20 minutes of anodizing time, and then becomes asymptotic. The graph indicates breakdown values of 1 200 volts, with two faces adjacent. The insulation strength, therefore, of the single anodized layer is approximately 600 volts after a 20-minute anodizing time.

Abstract No. 2256
Feb. 1957

NORTH-EASTERN CENTRE: CHAIRMAN'S ADDRESS

By J. CHRISTIE, Member.

'ACTIVITIES ASSOCIATED WITH THE MANUFACTURE OF SWITCHGEAR'

(Abstract *of Address delivered at* Newcastle upon Tyne, *8th October*, 1956.)

This is a wonderful age. Because of the many spectacular developments which are taking place, however, little is heard of the equally important everyday efforts of the research, design or production engineer in the ordinary manufacturing organization. I thought, therefore, that it would be useful to review what is being done in the switchgear industry.

Mr. Christie is with A. Reyrolle and Co., Ltd.

Production

In recent years many changes have taken place in foundries, and shell moulding is one example of the way in which operations have been mechanized and new methods adopted. This process involves making thin shell moulds using a mixture of selected sand and resin which, after baking, is porous and therefore allows the hot gases to escape during casting. The accurate dimensions

and fine finish made possible by this method permit of substantial savings both in material and machining costs.

In the welding field the deep penetration obtainable by the automatic submerged-arc process minimizes the number of welding runs, the freedom from spatter eliminates the expense of weld cleaning, and the absence of arc glare contributes greatly to good working conditions.

Stud fixing by drilling and tapping has the disadvantage that, where oil-tightness is required, subsidiary caulking or welding may be necessary; alternatively, a thicker material than would otherwise be required may have to be used. By means of a special welding gun, studs or pins with treated ends can be welded directly into position even on comparatively thin plates without the risk of subsequent oil leakage, and this is another way in which welding is saving time and material.

Surface treatment of materials is an important manufacturing process which finds applications ranging from the initial cleaning of a material to the production of the final finish. Sand blasting is a well-known method of removing scale and rust, but it usually necessitates taking the job to a sand-blasting booth. In contrast to this, a portable sand-blasting plant is now available in which, by means of a special nozzle, the shot is confined to the immediate area of surface being treated and is then automatically returned to the machine for re-use.

Turning from sand blasting to the final treatment of a contact surface, it is now usual practice to silver-plate such surfaces to avoid oxidation and consequent trouble due to overheating. In cases where this plating must be done *in situ*, portable equipment is available by which a layer of silver 1–$1\frac{1}{2}$ mils thick can be electrochemically deposited in about 10 minutes.

Control boards call for a large variety of holes and slots in sheet-steel panels, and previously each panel had to be marked off, using templates, and a variety of machines were necessary for cutting the holes. These operations can now be carried out on a single heavy-duty turret press which operates with the speed of the punch press, allows the sheet steel to be quickly positioned, and has the necessary punches and dies immediately available.

A number of machines on repetition processes can now be made completely automatic by the addition of electronically controlled servo mechanisms, an increased output of more accurate work being obtained.

Materials

Epoxy resins are now available which, with suitable fillers, are impervious to moisture, mechanically robust, have good non-tracking properties and do not support combustion. These resins are finding an increasing application in replacing many of the types of insulating materials at present used in medium-voltage metalclad switchgear, while their mechanical properties, coupled with the ease with which they can be moulded, are opening up the possibility of a new approach to the design of this equipment. We now have some seven years' experience, and it is my belief that it will, in future, enable more reliable trouble-free switchgear of smaller dimensions and cost to be produced.

Among the many interesting proving tests which have been done, current transformers were subjected to faults equivalent to 250 MVA 11 kV, i.e. 13 100 amp, maintained for $\frac{1}{3}$ sec to establish how much damage is caused when a puncture or flashover takes place. These tests showed that the surface flashovers produced negligible damage, and in fact after the equipment was cleaned and retested it was found to be completely serviceable.

To simulate an internal puncture, a transformer with an artificial fault between the primary and secondary was tested, and it was found that, although a small portion of the moulding broke away, no fire resulted.

It is also well known that present types of voltage-transformer fuses are not very effective in protecting against a between-turns fault on the high-voltage windings, and, in consequence, a slow-growing fault of this type can cause overheating and may, with oil filling, cause a fire. A resin-insulated design, on the other hand, avoids the need for oil, and, I consider, strengthens the case for omitting the potential fuse which for years has been the aim of many engineers.

Of the many gases studied for use as an insulating and arc-quenching medium in circuit-breakers, sulphur hexafluoride seems to be the most promising. It is about 5 times as dense and 3 times as effective as air when used as a cooling medium, and has an electric strength of about $1\frac{1}{2}$ times that of oil when used with the clearances normally met with in switchgear. It is, in addition, colourless and odourless, and the products of decomposition resulting from an electric arc are non-poisonous.

The use of a vacuum tube for limited circuit-breaking duties is another interesting development. The extremely high electric strength of a gap in a vacuum is well known, but it has not been possible previously to take advantage of this for circuit-breaking purposes because the gases produced by the contacts during arcing destroyed the vacuum.

It is now possible to de-gasify tungsten arcing tips, and with the improved vacua now obtainable this difficulty is overcome. In a practical design, tungsten butt contacts are enclosed in an evacuated glass envelope and operated through a metal bellows, the contact travel being of the order of $\frac{5}{32}$ in. On electrical pressure test it has been found that flashover takes place externally over a distance of about 8 in rather than across this small contact gap. Designs of this type are already in service in the United States for interrupting line-charging currents and banks of capacitors.

Transistors made of germanium are now available, and because of their small size, robustness, long life and simplicity it is considered that they will replace, with advantage, thermionic valves in such applications as carrier protective systems.

Time does not permit of a description of what is being done by the switchgear engineer in connection with the instrumentation and control of nuclear power reactors or the applications of the many new synthetic materials that are now available. In the latter field, however, it may perhaps be worth mentioning that when polythene is subjected to high-energy nuclear radiation the changes which take place in the molecular structure increase the melting-point and improve its resistance to oil. At the moment, however, little is known about this new development.

Measurements and Testing

The success of research, development, testing and quality control depends to a large extent on being able to measure or obtain a picture of what is taking place.

For instance, in the quality-control field, steel plates can be checked for layering by means of a device which applies a repeated mechanical impulse to the surface of the material. In a normal plate these impulses are reflected from the reverse side, whereas in a faulty plate reflection occurs from the fault, and this can be detected by examining the frequency of reflection on a cathode-ray screen.

The highly penetrating nature of γ-rays is enabling important welds on air receivers and the like to be photographically examined, while normal X-ray examination remains invaluable for checking the assembly of cartridge fuses or the insertion of foil layers in condenser insulators.

The electrical design of bushings and insulators can be quickly and accurately checked by immersing a model in an electrolytic tank and plotting the actual stress field by means of probes.

The thickness of non-magnetic coatings, such as paint, on magnetic materials can be measured by means of a device

consisting of a permanent magnet and a flux-measuring instrument. After the zero has been adjusted on the surface of the virgin metal, the meter is placed on the coating to be checked and the thickness read directly from the scale.

A moisture meter is now available to avoid the troubles which can arise due to electrical equipment being packed in damp material. This consists of a bridge arrangement with two probes to which is applied a direct voltage, and the percentage of moisture can be read directly on the meter scale.

In the research field the suitability of Perspex for constructing experimental arc-control devices and tanks, and the recent development of photographic techniques capable of taking up to 400 000 pictures per second, are enabling arc phenomena to be studied in detail, particularly during the critical zero pause period. [High-speed films taken in conjunction with the development of circuit-breakers, and of an arc-gap for use with series capacitors were exhibited at the meeting.]

Finally, for proving complete circuit-breaker designs, larger testing stations are being built, higher voltages are becoming necessary in the laboratories, and many other facilities, such as icing chambers, are necessary to simulate actual climatic conditions.

Office Facilities

Modern requirements throw more and more work on to the office staff, and this emphasizes the need for more thought to be given to office routine and the use of mechanical aids wherever possible. Mechanization in the offices has been speeded up in recent years, and one very simple example which illustrates the basic principle involved in many of these devices is the electrically-operated typewriter, which, very quickly, reproduces the information recorded on a punched tape.

The same principle is being used to supply information to digital computers, which are finding many applications, from carrying out complex or laborious mathematical calculations to making up the payroll.

Many organizations also have their own particular form of simulator to enable them to investigate their specific type of problem more rapidly, a good example of this in the switchgear field being the network analyser, which is providing the answer to many complex power system problems.

In contrast, we do not have any such wonderful equipment for producing designs or drawings to order. The draughtsman can, however, be helped in a large number of comparatively simple ways, the overall effect of which is very valuable. For instance, in producing electrical diagrams many items are standard and have to be repeated frequently. These can be made available on transparent adhesive material and stuck on to the drawing in the required position, leaving only the connecting lines to be drawn in. The printing can be done on a special design of typewriter, and the final ink drawing on cloth can itself be reproduced direct from the paper drawing by modern printing techniques without the need for tracing and the re-checking which tracing involves.

The method of storing, locating and printing drawings can affect office efficiency appreciably. In the latest machine, of which we have as yet no experience, all drawings are reproduced on microfilms and mounted on cards punched so that any drawing can be located rapidly. This microfilm, when required, is passed into a high-speed automatic enlarger printer which uses a completely dry process and produces prints in a matter of seconds.

So far, we have dealt with the more direct mechanical aids to office personnel, but another equally important development which has been steadily proceeding over the years has been that of providing good working conditions, which, with modern lighting, heating, air-conditioning and sound-deadening equipment, have done much to improve physical and mental well-being.

Conclusion

In this short review I have endeavoured to show that the British switchgear industry is making use of techniques which can be considered as representing the contributions of many individuals in many branches of science and industry. While, taken separately, these may not appear important, their overall effect is such that without them our country's products would not be competitive in the world's markets.

Abstract No. 2255
Feb. 1957

NORTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By W. K. FLEMING, Member.

'ELECTRICITY SUPPLY AND THE PUBLIC'

(ABSTRACT *of Address delivered at* LEEDS, *2nd October*, 1956.)

From the earliest days of the industry, the public control, and indeed the public ownership, of electricity supply was much in the minds of various Governments and Government Committees, although not necessarily in the form eventually adopted under the nationalization Act of 1947.

The first Electric Lighting Act of 1882 authorized the Board of Trade to grant licences for the establishment of electricity undertakings by local authorities and, with the consent of local authorities, by companies. Local authorities were also given the right to take over in 21 years any companies so established, a term which was extended to 42 years in the 1888 Act, with further optional stages of ten years.

The report in 1918 of the Williamson Committee appointed by the Board of Trade, and the Electricity (Supply) Act, 1919, under which the Electricity Commissioners were established, were the beginnings of a movement towards the central control of the industry. A further and important stage was reached when, under the Electricity (Supply) Act, 1926, the Central Electricity Board was established to co-ordinate the generation and main transmission of electricity supplies throughout the country.

The complex problem of distribution was considered in 1936 by the McGowan Committee, who recommended the retention and utilization of the larger and more efficient undertakings and the absorption by such undertakings of the smaller and less efficient ones, with provision for the ultimate public ownership of all of them. This was followed in 1937 by a Government White Paper outlining proposals for the reorganization of distribution. One of the three bases of amalgamation proposed was the transfer of all existing undertakings to a new public distribution authority.

For many years before nationalization, therefore, the industry had been moving towards a position where some major reorganization on a national scale was inevitable.

It is of interest to consider the nature of the authority which assumed control of the electricity supply industry upon

Mr. Fleming is with the North Eastern Electricity Board (Harrogate Sub-Area).

nationalization. It is the type of authority known as the public corporation, and is not, of course, a Government Department as for instance is the Post Office.

Although the public corporation was the instrument chosen for the nationalization programme during the years since 1945, it was not, in its general character, a new type of authority. There had been a steadily developing trend over many years towards participation by the State in assisting, co-ordinating or controlling important public and national economic activities.

The Port of London Authority was a new type of public board set up in 1908 through legislation sponsored by the Government. After the First World War, interest grew in the future organization of public services of national importance, and in 1919 the Electricity Commission and the Forestry Commission were established. The first of the public corporations in the basic form as we know them to-day came with the establishment of the Central Electricity Board in 1926. This was followed in 1927 by the British Broadcasting Corporation and later by the London Passenger Transport Board, the British Sugar Corporation, and the British Overseas Airways Corporation. During the Second World War, the Scottish Hydro-Electric Board was formed, in 1943, as a public corporation, and from 1946 onwards, the creation of new public corporations has developed more rapidly.

Under the nationalization Acts, public corporations were set up to run major industries and services including coal mining, electricity and gas supply, inland transport and civil air transport, and we have observed the more recent examples of the United Kingdom Atomic Energy Authority and the Independent Television Authority. The full list of public corporations which exist to-day shows how wide is the influence and control exercised in some of the nation's most important activities.

There is no doubt that the development of the public corporation system in the electricity supply industry, as well as in other national industries and bodies of national activity, is a social and economic innovation in our constitutional life of the highest importance, and one which will have a profound influence in the future on our prosperity and standards of living. Every member of the community is therefore deeply concerned that this great change in public administration should succeed.

It is in the main principles underlying the conception of the public corporation that we see broadly where, in the field of industry or commerce, it takes its place between management by large-scale private enterprise on the one hand, and management by the Government (as in the case of a Government Department) on the other.

Public corporations are subject to certain powers of direction and control by the appropriate Minister, and are accountable to Parliament. There is, therefore, public control over major policy, which is not so in private enterprise. They are not, however, subject to full and continuous ministerial control and are largely independent in matters of current administration. This freedom of action in their day-to-day management was regarded as vital to their enterprise and success as commercial undertakings. On these points, the operation of a Government Department is less flexible.

Public corporations take different forms dictated largely by the nature of the services they provide, although no doubt there has also been some experimentation in method with a comparatively new system of organization. They also fall into well-defined classes according to their financial dependence on the State, from the corporations controlling the transport, electricity and gas industries, which have a large measure of financial independence, to those which derive the whole of their capital and operating income from voted moneys, as, for example, the British Broadcasting Corporation.

In the nationalized industries, the broad outline of organization is similar, with governing boards composed of members chosen by the appropriate Minister, not as representative of any sectional interest, but for their wide experience and ability in specified fields of activity. Another characteristic of the public corporations of the nationalized industries is that they are not profit-making bodies. This does not mean that they cannot, or should not, make a surplus, but by their nature they do not make profits as generally understood in private commercial enterprise. In other ways there are differences in the pattern and responsibilities of the public corporations—in the structure of the boards and the organization, in the distribution of functions between the Central and Area Boards, in financial and operational arrangements, and so on, again related to the requirements of the industry concerned.

With any enterprise, public or private, there is always present the compelling influence of public regulation. This can exist in a variety of ways; for example, the responsibilities and duties laid upon them by statute, the expression of public opinion and comment, favourable or otherwise, and the choice of the public in giving or withholding custom.

When a public body is established to take over and operate a national service it is subject to regulation of a special kind in that it becomes fully accountable to the public for its actions. The principal way in which public control is exercised over a nationalized industry is through its accountability to Parliament. This is exercised in practice by ministerial control in accordance with powers given to the Minister by statute, and by the general control of Parliament through the medium of parliamentary questions on policy and matters of public importance, and by debates. It has been hoped that with these safeguards the public interest would be preserved without interfering unduly with the administrative independence and managerial responsibility of the Boards.

It is apparent, however, that Parliament is not satisfied with the degree of public accountability which has so far been achieved by the methods at present available. It is felt by some, for example, that the position of the Minister in relation to the corporations and Parliament should be reviewed. A major difficulty has been the limited amount of time which Parliament has been able to give to debates on the nationalized industries, even on such occasions as the presentation of the Annual Reports and Accounts, which is the chief way in which information about the working of the undertakings is provided.

The question of accountability to Parliament has been considered by two Select Committees of the House of Commons. Some months ago, the Government announced their intention of appointing another Select Committee with, it is understood, wider powers of reference, and so a further stage has been reached in the attempt to secure a greater measure of parliamentary supervision.

The problem of finding the correct balance between parliamentary supervision and the independence of the Boards is urgent. A satisfactory solution will clearly be a great step forward in the successful development of the public corporation system. This solution may well come if it can be worked out in accordance with the spirit expressed by the first Select Committee in their report of 1953, when they said: 'It is essential that the Committee we are recommending will, when appointed, set up a tradition of conduct which will result in its being regarded by the Board not as an enemy, or a critic, but as a confidant, and a protection against irresponsible pressure, as well as a guardian of the public interest.'

One aspect of the public accountability of the nationalized industries is the extent to which they have been brought into the limelight of public opinion; in many ways a greater interest is

taken in their affairs by members of the public, the Press and other organs of public opinion than was the case before nationalization. A favourable public opinion of the organization and its service is clearly a result which any institution, public or private, must strive to achieve, and the more enlightened and educated this public opinion is, the greater will be the success of the administration. What are the elements of such a public opinion? They must surely be public confidence and public understanding—public confidence in the aims, the policies and the conduct of the organization, and public understanding based on the dissemination of knowledge and information. Is there a need here for a still closer relationship between the public and the nationalized industries?

One of our national characteristics is a tendency to criticize Government Departments and public authorities. Whether this springs, as Bagehot wrote, from 'the natural impulse of the English people to resist authority', or from what may be called the popular conception of bureaucracy, it is a democratic attitude which in itself is quite healthy. Criticism can be helpful if it is reasonable and informed.

We should see public criticism as an expression of public opinion to be met, not by resentment, but by responsiveness and enterprise. Viewed in this way, it can indeed be a spur to greater efficiency and a safeguard for the public in the nationalized industries corresponding to other incentives in private enterprise. In this and other directions where it is necessary to inform the public and to interpret their views and rightful needs, the function of public relations in a large-scale organization is important.

Public relations has been defined and interpreted in many different ways, partly, no doubt, because it is composed of so many elements. The aim at any rate is basically simple, for it is no more than the establishment of confidence and mutual understanding between an organization and its public. The success of the public relations of any organization depends very much on the conduct of all the individuals employed by it—conduct in the way they do their jobs, in their attitudes to the employer and to the public. Conduct gives an organization character, and the public judge an organization by its character.

No matter how efficiently we plan and carry out the many activities which eventually bring us into personal contact with the public, the full value of these efforts is not realized if the employee does not leave a good impression when service is rendered, and unless the relationship between the employees and the consumers is satisfactory. The basis of this good relationship lies in good relations between management and employees, and it is here, in any organization, that public relations should begin.

Now, more than ever, the human factor in industry is dominant. If we think again of the aim of public relations, we see that there must also be a two-way flow of communication and co-operation between management and men. The larger the organization, the more complex are the lines of communication and the more difficult is the problem. The objective, however, is clear: that management, with inspired leadership, should strive to understand and satisfy the reasonable needs and desires of their employees, so that they may work and live, with purpose and dignity, to give the fullest expression of their skills in public service.

A distinguished Past-President of our Institution, the late Sir Clifford Paterson, once said that 'every association, in common with every individual, possesses two values: one, a material value, corresponding to what it achieves, the other, spiritual or psychological, representing the kind of influence it exerts. As a rule, the material value, being more directly obvious, is the more easily assessed, but it does not follow that it is the more important of the two. In fact, is there not a well-founded and traditional belief that for individuals, at any rate, it is the influence they have exerted that will weigh heaviest at last, for good or ill, in the scales?'

The electricity supply industry will be judged by these two values: the material value expressed in the way it meets the needs of the public with an efficient and economical service of electricity, and the psychological value implicit in the influence it exerts for the public good—the good not only of the public it serves, but of the individuals who man the industry.

Abstract No. 2266
Feb. 1957

NORTH-WESTERN CENTRE: CHAIRMAN'S ADDRESS

By T. E. DANIEL, M.Eng., M.I.Mech.E., Member.

(ABSTRACT *of Address delivered at* MANCHESTER, *2nd October*, 1956.)

The Address opened with a reference to some of the earliest Chairmen of the Centre such as Ferranti, Hopkinson and Pearce, and then proceeded to show the progress that had been made by the North Western Electricity Board since its inception in 1948. In spite of an increased cost per unit purchased of some 32%, the increase in revenue per unit sold was only 21%, and the price of coal during the same period had increased by 53%. These figures tell their own tale—that the bringing together of the many undertakings has been for the general good of the Area.

Consideration was then given to the measure of standardization achieved in the Area of the Board, which is responsible for distribution. Certain definite trends were obvious, and the work of standardization follows the trends. It is the policy of the Board to adopt national standards.

Standardization of System

Fortunately most of the non-standard-frequency systems had been changed to 50 c/s by 1948.

Standard voltages were agreed, namely 33 000, 11 000 and 415 volts between phases. A substandard of 6 600 volts has had to be accepted for the time being for certain areas where it was impractical to increase the voltage owing to unsuitable cable networks.

A standard phase relationship was fixed, but here again economics necessitate certain variations, at least for the time being.

Short-circuit currents on any high-voltage network are limited to 13 100 amp. The strenuous application of this limit has resulted in the installation of reactors in many densely loaded areas, and these have proved economic.

System Design and Development

The abolition of the boundary lines between the previous undertakings gave a completely new approach to the design of network extensions, and the modification to the bulk supply tariff, whereby the charge was made on the simultaneous maximum demand of all supply points, permitted of greater flexibility in design and operation.

Other important factors affecting design have been the gradual

---

Mr. Daniel is with the North Western Electricity Board.

closing down of small generating stations, and the need to transfer heavy loads for greater distances. The advent of the 275 kV Grid is already having its effect on the design of 33 kV networks.

Other things being equal, the cheapest scheme for the industry as a whole is now the one that has been adopted, irrespective of the division of cost between the Central Electricity Authority and the Electricity Board.

On the 11 kV networks there has been a trend to more high-voltage distributors, with more injection points into the medium-voltage networks.

It was common practice to construct a substantial substation building to house an h.v. switchboard and two 1 000 kVA transformers, with large section distributors for an area of supply of up to 140 acres, but several single-transformer substations would be provided to-day, equipped with a 500 or 750 kVA transformer, some installed outdoors without any h.v. switchgear and each supplying an area of not more than 20 acres with distributors seldom exceeding $0 \cdot 1\,in^2$ in cross-section.

A measure of austerity has crept into system development as compared with pre-war practice, and more plant has been installed outdoors, thus doing away with the need for buildings and the simplification, or elimination, of switchgear.

But for the wise and generous planning of the former undertakings it would not be possible to meet the heavy demand on the networks. More 33 kV mains and additional injection points have enabled extra use to be made of the networks.

On the 11 and 6·6 kV systems in the towns the trend of development is towards open rings or an interconnected system so split as to operate as radial feeders with standby. In the rare event of a fault, one or more substations may be shut down but supplies can be restored in a reasonable time by operational switching, and the saving in capital cost by the omission of the protective gear and automatic circuit-breakers, which would be necessary to provide automatic 'firm' supplies, is very considerable.

Entirely new networks designed for an after-diversity demand of 3 kW per consumer are constructed for very little more money than their pre-war counterparts, in spite of the immense rise in costs. This is achieved by making greater use of the copper, by simplifying, and so cheapening, processes and by standardizing on simple but efficient equipment. We are still searching for a cheaper type of unit than the conventional ring-main oil circuit-breaker for connecting a network transformer to the h.v. mains.

33 kV Switchgear

The Board uses two basic types of 33 kV switchgear, namely the conventional outdoor type and the indoor metalclad single-busbar non-phase-segregated gear. Every effort is made to use gear to a standard drawing, including protective schemes, cable boxes and the like. A rated breaking capacity of 750 MVA has been adopted as standard.

Control and alarm schemes are covered by standard diagrams incorporated in the specification, as also are standard protective schemes and bus-zone tripping diagrams. Cable boxes with removable front covers and gland plates are called for, since it has been found to be a great advantage to lay the cable directly into the cable box. A standard height of 7 ft 3 in and a light aircraft-grey finish have been adopted for control and relay panels. These and other detailed requirements are embodied in a standard specification, in which only the schedule of variables relating to a particular substation has to be filled in.

The single-switch outdoor substation, with load-breaking isolators, has been used to control two incoming lines and two transformers, and an interesting development of this is the application of the same arrangement to indoor 33 kV metal-clad gear. The arrangement achieves nearly a 50% saving in the capital cost of switchgear as compared with the conventional switchboard comprising 5 oil circuit-breakers.

11 kV Switchgear

It was decided to standardize on single-busbar metalclad gear on account of its compactness and its operational convenience and safety. The British Electricity Specification covering 13 standard units is now used.

The number of types of protection was reduced, and the 14 current-transformer ratios were reduced to one dual ratio for distribution transformer circuits, and to two alternative ratios for feeder circuits.

By joint consultation with the manufacturers, weakness in earlier designs has been eradicated, improvements have been made in the design of interlocks, in safety shutters and in earthing equipment in particular, whilst the modern designs have made this class of gear exceedingly safe and convenient to operate.

There is a renewed interest in auto-reclosers and in switch-fuses.

Ways of reducing the cost of switchgear are being investigated; oil switches are being used in place of automatic oil circuit-breakers, and ring-main units are being installed out of doors. Switch-fuse equipments to control distribution transformers would further reduce costs, but so far no manufacturer has been able to meet the Board's requirements.

Transformers

A decision to use 10 MVA transformers for 33 kV was made by selecting the largest substation which would permit two transformers, each with 10% reactance, to operate in parallel, without exceeding a fault level of 150 MVA on the lower-voltage side when they were supplied from a 33 kV busbar operating at a fault level of 750 MVA. A standard tapping range of $+4\frac{1}{2}\%$ to -15% in thirteen $1\frac{1}{2}\%$ steps was adopted, and ratios of 33/11 and 33/6·6 kV with either delta/star or star/star windings were adopted.

Analogous with the control and alarm circuits for switchgear are the tap-change control circuits for transformers, and a standard scheme, suitable for up to three transformers operating in parallel and with provision for supervisory control, was agreed with each supplier. Automatic voltage control with compounding (line-drop compensation) to give a rising voltage characteristic of +5% at full load is also standard.

We shall undoubtedly want a larger transformer in the future, probably having a naturally cooled rating of 15 MVA and an assisted cooled cyclic rating of 22·5 MVA.

The choice is limited both by fault level considerations and by the current rating of the associated lower-voltage switchgear. Such a transformer would require 1 200 amp switchgear at 11 kV or 2 000 amp switchgear at 6·6 kV. Standard sizes for 11 and 6·6 kV transformers are 500 and 750 kVA.

Substation Design

Standard switchgear and transformers materially assist the standardization of substation layout and buildings.

With the larger substations, the 33 kV switchgear building is sectionalized by fireproof walls on either side of the bus section switch, and the cables are led into the building via ducts terminating at ground level below the gland on the switch unit. Carbon-dioxide fire-fighting equipment is installed in all the 33 kV substations, the CO_2 capacity giving 50% concentration on the first discharge.

The 33 kV substations are provided with a control room, and each circuit has its own control cubicle. The 11 kV substations are, however, much more austere, and the control equipment is

mounted on the switchgear. Control panels are provided for incoming transformers only where the protective system is of necessity more complicated.

Cables

A standard size of 0·3 in² was adopted for 33 kV cables, with the possible use of 0·2 in² for sparsely loaded areas. In practice it has been rarely found that the substandard size has been required. Only 11 kV cables are used on both 11 and 6·6 kV systems, the sizes being 0·06, 0·15 and 0·3 in². In the medium-voltage range the sizes are 0·04, 0·06, 0·1, 0·15 and 0·25 in².

The use of red p.v.c. tape immediately over the wire armouring of the cable has now superseded red impregnated hessian tape as a means of identifying high-voltage cables.

The application of cyclic loadings to transformers indicates that in the future a cable having a rating of 30 MVA will be required. It has recently been decided to install two 0·2 in², 3-core gas-filled cables operating at 33 kV over a route length of some 4 000 yd with stranded aluminium conductors.

Overhead Lines

In the design of overhead lines, careful consideration was given to the use of the unearthed type of construction following the adoption during the war period of the B.S. 1320 type of line, but employing conductors having cross-sections in excess of those permitted. The Ministry of Fuel and Power have allowed relaxations for the use of this unearthed type of construction for conductors up to and including 0·15 in². This form of construction has also been adopted for 33 kV working, and although the first line of this type was erected with steel cross-arms, wooden cross-arms have now been very largely adopted.

The rapid increase in the cost of copper in recent years has forced consideration of the use of steel-cored aluminium for overhead line conductors. In view of the larger cross-sectional areas required for equivalent current-carrying capacity, consideration has had to be given to the use of shorter spans and heavier poles.

There are many reasons in favour of reverting to copper conductor lines, and this will be done as soon as price comparisons justify the change.

Conclusion

Nuclear power will undoubtedly play a big part in the production of electricity in the future, but it is confined to steam raising, and young engineers are reminded that electricity supply engineering will provide a worth-while career for many years to come.

Modern civilization depends more and more upon the work of the electrical engineer, who by his inventions and devices has made possible what was hitherto thought to be impossible. Progress has been rapid, and the future will reveal, still more, the hidden sources of power and the intricate working of nature which can be used for the benefit of mankind, but which could be used for its destruction in the hands of unscrupulous men. Man does not live by bread alone, and the temptation to regard material things as an end in themselves must be resisted because the balanced personality requires also the contemplation of spiritual things. We neglect these at our peril.

Unless this truth is fully understood the work of the electrical engineer can never have its true value in improving the lot of mankind, and that which should have been entirely beneficent may contain too much of that which is devilish. As an Institution we can do very little about it, but as individuals we can do much, if we will; and the world is made up of individuals.

Abstract No. 2343
Feb. 1957

NORTHERN IRELAND CENTRE: CHAIRMAN'S ADDRESS

By DOUGLAS S. PARRY, Member.

'A FEW REMARKS ABOUT SWITCHGEAR'

(ABSTRACT *of Address delivered at* BELFAST, *9th October*, 1956.)

It will be remembered that, as far back as the 'twenties, main station switchgear, either in stone cellular or armourclad form, was installed without very serious regard for breaking capacity, if only for the reason that no reliable means were available for ascertaining values, save inspired guessing.

As was mentioned this year at the Conference on Large Electric Systems (C.I.G.R.É.) in Paris, there is a current demand for switchgear of ever-increasing breaking capacity, owing to the larger and larger sizes of alternators and station capacities, the paralleling of systems, and a demand for yet even greater reliability in the maintenance of supplies. Outage time must be reduced to an absolute minimum, even in cases of serious disturbance. Large circuit-breakers must be capable of reclosure under major fault conditions. Maintenance has become a matter of primary importance to be carried out in an absolute minimum of time. I think that we in Great Britain have risen to this demand.

It was not until about 1930 that there were available to switchgear manufacturers any testing plants whatsoever and then only capable of testing up to 1 500 MVA at a maximum. To-day we not only have high-power research stations, but facilities for very-high-voltage impulse testing, and means of finding out, accurately, the actual breaking capacity demanded of switchgear at any point on a complicated network—I refer of course to network analysers.

Under the heading of large switchgear must be included those circuit-breakers suitable for service on voltages up to 380 kV with a prospective breaking capacity of 10 000 MVA. Other accepted ratings are 5 000 MVA at 220 kV and 7 500 MVA at 275 kV. So far, the largest switch built in Great Britain, tested, installed and in service, is a 275 kV 7 500 MVA equipment. 25 000 MVA circuit-breakers are already a reality abroad, with even higher ratings on the horizon. Very large breakers are usually erected out of doors, but there have been several notable indoor installations of recent date, particularly at new power stations. Outdoor switchgear installed indoors permits easier maintenance, for example, less cleaning and painting, and in a particularly wet, humid and salt-laden atmosphere, gives some extra measure of safety.

It is generally accepted these days that high-duty equipments should have a 3-cycle clearance time, on a 60-cycle basis, and the latest developments of reclosing mechanisms have enabled an overall clearing and reclosing performance to be carried out in 18 cycles. These are indeed severe duties, bearing in mind that in these times a trip coil must be energized, moving parts must be

Mr. Parry is with A. Reyrolle and Co., Ltd.

accelerated from rest, contacts must separate, and the arc be extinguished—all in about one-twentieth of a second.

A High-Power Research Station

To-day we are able in Great Britain to carry out full-scale testing which bears little relation to past performance. The latest station, built in 1954, will prove almost any equipment likely to be designed in the foreseeable future. The prime object of the station is to give maximum output at voltage ratings up to 380 kV in single-phase tests, although the plant will also give 3-phase short-circuits at very high outputs up to 275 kV, substantially full recovery voltages being maintained.

The station contains three machines, all of very low reactance, two on 50 MVA and one on 60 MVA frame sizes. They weigh about 100 tons each. All are arranged for single-phase connections of the 3-phase windings in order to achieve the maximum possible single-phase output. Each is driven by a 1 200 h.p. induction motor which runs at 3 000 r.p.m. Various voltages are selected by changing the generator and transformer connections, the power factor of the test circuit being controlled by series reactors and resistors.

The short-circuit generators are paralleled on the e.h.v. side of the transformers to avoid the enormous currents which might otherwise flow in the event of a generator fault—for this reason an auxiliary synchronizing tie in the form of two single-phase transformers is necessary to hold the machines in parallel prior to the application of the short-circuit.

Immediately before the application of a fault, the motors are switched off, and the fault is then applied by means of ganged star-point making switches. These switches are designed to precision limits to close at any selected point of the voltage wave. They are capable of making currents up to over 150 kiloamperes peak.

There are plenty of facilities for dealing with fires when circuit breakers are occasionally tested to destruction.

Impulse Testing

The purpose of impulse testing is to ensure that equipment will withstand voltage surges arising from any faulty switching operations, or those produced by electrical storms. In order to produce the high unidirectional voltages required, an impulse generator is used, operating on the principle of charging a number of capacitors connected in parallel and then discharging them in series, the switching being effected by spark-gaps. The largest impulse generator at present installed in Europe is a 4 MV 18-stage 2-column equipment with an energy rating of 285 kW-seconds, d.c. charging 220 kV per stage.

Network Analysers

The use of network analysers for the study of electrical power system problems is now established, and they are almost invariably used for computing short-circuit values at various points, voltage regulation, load distribution and synchronous stability, all previously involving almost insuperable calculations, and endless time.

They are basically of two main designs. One is the impedance type, in which the impedances of the power system are represented by impedances in the analyser. The other is the analogue type, in which the impedances are represented, for example, by transformers. Power studies may also be effected by setting up the equations of the system and solving these on one of the many forms of digital computer. [Design and operation details were then given.]

Types of Large Circuit-Breakers

There are to-day three main classes of switchgear which are in general use:

Bulk-Oil.—Bulk-oil or dead-tank breakers are of time-honoured design, but still find favour with a number of engineers. In order to effect a considerable saving in oil quantity, and particularly having in mind servicing time, a distinctive lenticular shape of tank has been adopted by at least one manufacturer, although others still favour the more conventional cylindrical shape. With either type a manhole is provided on the side, which allows an operator to service the contacts and any other details whilst standing within the tank.

The operation of a bulk-oil circuit-breaker is, I am sure, fairly generally understood, and these very large units are no exception to the established principle—making use of arc-control devices and usually resistance switching. The number of series breaks per pole is dictated by voltage and breaking-capacity duties.

Air Blast.—Circuit-breakers of air-blast design have now been in service on large networks, both in Great Britain and abroad, for more than fifteen years. Development was originally carried out to meet a demand for an oilless equipment of high breaking capacity. They are particularly suitable for very-high-voltage service, and tested breakers are now available for the highest rated breaking capacities demanded. Operational experience has shown that the air-blast design of breaker has entirely reliable characteristics, such as insulation security, high speed of operation, effective control of switching over-voltages, minimum burning of contacts, and particularly speed and ease of maintenance. Breakers can be arranged, without adding greatly to either cost or complication, with auto-reclosing features, which duty, as already mentioned, demands exceptionally high speed of operation.

The voltage and breaking capacity ratings of breakers are essentially controlled by the number of air-blast turbulators. For example, a 132 kV 3 500 MVA breaker would consist of four turbulators arranged in series vertically. In the case of, say, a 275 kV 7 500 MVA unit, multi-break construction is also used, with six breaks in series, but connected horizontally instead of vertically. This arrangement economizes on overall height and gives greater rigidity of construction.

Very briefly, in the operation of breaking, the arc is initiated by the separation of moving contacts, and transferred by air blast to arcing electrodes within an arcing chamber, and thence through a metal nozzle or Venturi orifice, where it is extinguished at the first current zero. A few hundredths of a second after arc extinction, a series isolator operates, giving safe clearance distance and the ultimate open-circuit.

Compressed-Air Equipment.—The compressed air equipment must be absolutely reliable and foolproof. Many air-blast circuit-breaker installations and their ancillary air systems are entirely unattended, except for routine weekly inspection. Air compressors and motors are usually supplied in duplicate, together with main air-storage receivers, so that air is always available. Air from the compressors is taken through after-coolers, water and oil filters, and into the main receivers, where it is stored at 600 lb/in^2; from there it goes through reducing valves, reducing the humidity sufficiently to ensure that no moisture is present; and then into a ring-main system feeding the local receivers, one for each circuit-breaker, the pressure now being about 330 lb/in^2. A local receiver stores sufficient air to give one break-make-break operation. Air is also drawn from the ring main, after reduction to practically atmospheric pressure and having negligible humidity, for use as conditioning air which is passed in a continuous 24-hour service over all internal insulation surfaces. Check visual flow meters are provided.

Small Oil.—This class of circuit-breaker has now been developed and proved in service for upwards of eighteen years and is to-day being installed in increasing numbers, both for

controlling the main circuits at power stations and on cable and overhead-line distribution networks. It is designed primarily for outdoor service. Whilst at one time it was thought that the very highest voltage and rupturing-capacity duties would be met by designs other than small oil, to-day units have already been connected for 5 000 MVA at 220 kV.

Experience has shown that a modern small oil-breaker can be left energized indefinitely either open or closed with full voltage applied. I mention this, as many years ago it was thought advisable to isolate, when left open and alive. In line with British Standard recommendations, an inspection should take place as soon as possible after the occurrence of a fault. This, of course, applies to all types of switchgear.

Small oil units are particularly suitable for automatic reclosing duties; all moving parts are light in construction, and dead times are short. Oil quantities in, for example, a 33 kV 1 500 MVA equipment are 21 gal in the circuit-breaking compartment and 69 gal for insulation; in 110 kV 2 500 MVA equipment, 39 gal and 150 gal respectively. These figures apply to 3-phase breakers; they bear little relationship to other classes of breaker for the same duty. With this class the oil in which contact separation takes place is within a Bakelized-paper tank or other container, and is physically separated from the main insulating oil. This means that insulation under permanent stress to earth is immersed in oil which is never carbonized. Circuit-breaking is done within turbulators between fixed and high-speed moving contacts, the latter being hollow and of such design that as they separate they inject a column of clean oil into the turbulator.

[Details were given and lantern slides shown, demonstrating the operation of the three classes of switchgear.]

Maintenance

At my peril, may I before concluding, make a few remarks on maintenance, and ask for licence to bring in lower voltage and somewhat smaller switchgear.

We all expect good and necessarily expensive switchgear to give long and faithful service. Very well, switchgear is to some considerable degree disarming, in as much as it nearly always appears quiet and well behaved. 'Don't worry about me', it seems to say, and even when it has to work, which is seldom, it clears tremendous amounts of power, with little more than a 'click' and a 'woof', and for this very reason it asks for generous inspection and maintenance.

As soon as gear is installed, natural forces combine to destroy it, particularly in present-day industrial atmospheres, laden not only with solid dirt, but with gases, sulphur and acids. I have during and immediately after the war years seen mechanisms corroded solid, and have had relays disintegrate in my hand. We have done all we can for you in the selection of materials and their finishes, and ask you to correct both oxidation and corrosion in their infancy.

On outdoor high-voltage gear, bushings can give little trouble, as all internal insulation is sealed against the ingress of moisture. The porcelains themselves, however, need attention. In particularly dirty country, anti-fog insulators may be used; the creepage distance is then much greater and the underside of the insulator is protected from direct rain. The long-term effect of normal voltage on insulators subjected to atmospheric pollution, fog deposits or salt spray can eventually cause a flashover; please keep them clean. Outdoor gear should be safely hosed down under proper supervision, which is by far the quickest way.

In all large outdoor switchgear a general and extensive check should be carried out once a year, including the compressors and the air system as a whole. It is most important to avoid the entry during maintenance of any moisture into the circuit-breaker or contamination of any of the parts. Turbulators, for example, if removed for more than three or four hours, should be immersed in oil; similarly in wet weather, or if entry of moisture is suspected within the breaker, the oil should be circulated at 70° C for as long as is practicable and preferably for as long as 24 hours.

Remember at all times that high-pressure air is lethal. Do not work on any part of an air system whilst it is under pressure. Reduce to atmosphere and isolate the apparatus upon which work is being carried out.

We should also bear in mind that high-voltage air-break isolating switches are not intended to break circuit under appreciable load, and if they are put to such use, dangerous surges may result, with violent arcing and burning. They can fail even when breaking magnetizing current.

I come now to my plea for the inclusion of the smaller sizes of bulk oil gear, say up to 1 500 MVA breaking capacity. The few pointers I am now going to mention are simple, but in my personal experience each has been the cause of trouble, some serious. Always examine a circuit-breaker as soon as possible after fault clearance. Carry out regular inspection and maintenance and keep faithful records. Every circuit-breaker and relay in the system should be operated at least every six months, and then several times. Oil moving parts in their open and closed positions. Make sure tripping plungers are free. Never operate circuit-breakers without main and dashpot oil; otherwise serious damage can be done which is not always immediately apparent. Inspect tank linings for small burns. Be sure you are on the correct shutters or locking-off doors, and I say this with the greatest respect, having in mind that interlocks can fail or be deliberately defeated, and operators may well be working under stress. Renew damaged tank gaskets: after a severe duty a faulty gasket can be a serious danger.

Remember that a spare circuit-breaker, not excited, does not keep as warm and dry as one carrying load, and needs to be dusted and dried before plugging in. Clean insulators under oil—they collect sludge. Voltage-transformer oil should be sampled every two or three years, and the tank thoroughly cleaned out if the oil is replaced. After testing, be sure you have removed all test and earth connections. Do not unnecessarily disturb the settings of any switchgear components, particularly mechanisms and protective devices. If you must, maintain the original settings.

Indoor bushings are generally of synthetic-resin-bonded paper, and if treated with proper respect give little trouble, but mechanical damage must be avoided. An insignificant scratch may be sufficient to allow ingress of moisture, flow of leakage current, heating and eventual breakdown. Tracking can also be started from a slight scratch. Bushings may be affected by prolonged exposure to humid surroundings; a relative humidity exceeding 80% is near the danger point. Please adequately heat and ventilate your switch stations.

In important installations from 33 kV upwards, annual power factor tests are well worth while. The actual values are not as important, within limits, as an abnormal rise or change between testing periods. The usual method is to use a Schering bridge, and to compare the insulator under test with a practically loss-free condenser. On very important installations, particularly busbars, methods are available for testing insulators on load.

[Mr. Parry concluded by expressing to his friends and colleagues his appreciation of their assistance in the preparation of his remarks.]

Abstract No. 2323
Feb. 1957

SCOTTISH CENTRE: CHAIRMAN'S ADDRESS

By Professor F. M. BRUCE, M.Sc., Ph.D., A.Inst.P., Member.

'POST-GRADUATE RESEARCH: ITS OBJECTS AND SOME ACHIEVEMENTS'

(ABSTRACT *of Address delivered before the* SOUTH-EAST SCOTLAND SUB-CENTRE *at* EDINBURGH *2nd October, the* SOUTH-WEST SCOTLAND SUB-CENTRE *at* GLASGOW *3rd October, and the* NORTH SCOTLAND SUB-CENTRE *at* DUNDEE *11th October and at* ABERDEEN *12th October*, 1956.)

In these days of large industrial research and development organizations, what might be defined as research in the classical manner is now given a prefix such as 'fundamental', 'long-term' or 'academic', and the experience of post-graduate work leading to a higher degree is invaluable to the small proportion of graduates who exhibit the particular aptitudes required for such work. They will later be concerned with seeking to establish reliable theories or data for imperfectly understood physical phenomena, all the emphasis being placed upon the search for true facts, and without any defined objective such as always lurks in the background of 'industrial' or 'applied' research. They must develop a good sense of logic in planning their work, a power of analytical judgment, and that absorbing interest which alone can produce the initiative required.

Some seven years ago, the Governors of the Royal College of Science and Technology approved a programme for the establishment of a research school in the Department of Electrical Engineering, and this has now been operating effectively for some years. In particular, very comprehensive facilities for research at high voltages have been made available.

For this Address, I have chosen to deal, in a general way, with two of the main programmes of research—the mechanism of the spark discharge in air, and power follow-current phenomena.

Spark Studies

The introduction of high impulse voltages, and suitable oscillographs for recording the very rapid change of voltage with time, provided a new means for studying the mechanism of sparkover. It was soon found that gaps exhibited time-lag phenomena, as instanced by breakdown occurring on the tail of the wave and not at the crest. For a given gap and impulse waveform, there is a range in the crest values of the impulses applied to the gap over which the frequency of breakdown for a number of applications varies from 0 to 100%. The zero level could be taken as the threshold of breakdown for the given conditions, and an increased frequency of breakdown required a higher voltage (or an 'over-voltage') for which the point of breakdown moved from the tail towards the crest of the wave, indicating a reduction in the time-lag of the gap.

More fundamental studies of time-lag phenomena were undertaken with direct voltages, giving rise to the division of time-lag into statistical and formative periods. The former can be eliminated by adequate irradiation, leaving the latter as characteristic of the breakdown mechanism. It was found that the formative time could be reduced, apparently without limit, if sufficient over-voltage was applied.

Whether with direct or impulse voltages, the time-lags were of the order of microseconds or very much less, and these low values could not be explained by the processes involved in the Townsend theory as then appreciated, unless at low values of $p \times d$. For these reasons, the *Kanal* or streamer theories were proposed as the breakdown mechanism[1] for the high-pressure discharge, and it was believed that transition from the Townsend to the streamer mechanism occurred at some critical value of $p \times d$.

For reasons previously published,[2] I was not satisfied with this transition in the mechanism or the qualitative arguments of the alternative theory, and further investigation of it was one of the first items on our programme. The uniform field, which is the basis for studies of this type, is produced between parallel plane electrodes having the edges suitably curved to ensure that breakdown, within the working range of spacings, always takes place in the uniform-field region. At excessive spacings, of course, the maximum surface gradient is developed at the curved edges, giving non-uniform field discharges. There have been various designs of electrode contour to produce these conditions, and it is perhaps natural that an atmosphere of some rivalry has appeared in the past, and may well do so in the future.

In fact, the shape of the edges is immaterial, provided that it can be demonstrated that the sparks have the characteristics of breakdown in a uniform field. The edge contour does have secondary effects such as determining clearance required from surrounding objects, overall dimensions, and maximum permissible spacing. For my part, I continue to use the Stephenson profile, with which I have worked for more than 20 years.[3] This is the only type of electrode for which it has been established that, for alternating voltages, the sparkover-voltage/spacing characteristic can be expressed by a single equation to an accuracy within $\pm 0{\cdot}1\%$. The equation applies to electrodes of any overall dimensions and is independent of polarity. I am glad to announce that our work in Glasgow has already established that the equation applies equally to direct and impulse voltages of either polarity. These characteristics are to be expected in truly uniform-field breakdown.

The time-lag for these uniform-field gaps was investigated with stable direct voltages. An approach voltage some 2% below the sparking voltage is applied, and on this is superimposed a rectangular pulse voltage—by measuring this voltage separately, the pulse magnitude can be expressed very accurately as a percentage of the total. The magnitude of the pulse is increased by small increments until breakdowns occur, the time from application of the pulse to breakdown giving a measure of the time-lag. This work has now been extended to gap spacings up to 4·0 cm, the results being consistent with data previously published[4] for smaller spacings. The time-lag/over-voltage curves are repeatable, and independent of electrode dimensions provided that the field is uniform. At low over-voltages (about 0·1%), time-lags of the order of hundreds of microseconds are obtained, and a plot of time-lag/spacing for constant values of over-voltage yields a series of straight lines passing through the origin. These are characteristics of the Townsend theory as now understood,[5] and have been determined for values of $p \times d$ up to 3000, or 15 times as high as once thought, and the range is being extended.

The direct-voltage time-lag data reveal the limitations inherent in using impulse voltages only, for such studies. In that case, the 0% criterion has to be taken as the threshold of sparking, but because the peak voltage only lasts for times of the order of microseconds, when at or near to the crest value of the waveform, this impulse datum is really a value of over-voltage sufficient to ensure that the time-lag has already been reduced to a value lying within the duration of the peak voltage of the waveform. The true threshold voltage is the direct-voltage datum, and will have a lower value. Using a 0·2/240 impulse wave (this being

Professor Bruce occupies the Chair of Electrical Engineering at the Royal College of Science and Technology, Glasgow.

an even closer approximation to direct voltage than the standard 1/50 wave), data have already been published[4] to account quantitatively for the apparent discrepancy between impulse and direct-voltage time-lag values.

Photographic studies of spark discharges have been used in the College for some years, the first series being based on the method of suppressed discharges described by Torok. The technique was modified by using a fixed loop to control the reflection time, but inserting a series gap, the time-lag of which was varied to control the time to suppression in the main gap. This was applied to sparking between spheres, and revealed a number of important characteristics in the development of the discharge.[6]

A uniform-field gap, especially when highly 'over-volted', reveals auto-suppression. This is due to the very small formative time-lag under these conditions, so that several channels are likely to develop at the same time, and the first to be completed then suppresses the others. By using a camera technique giving two orthogonal views, the spark position relative to the electrodes and to each other could be identified. One of the most interesting photographs was that showing a rectangular step in the path of the spark.[6]

Another means for studying the mechanism of sparkover is in the measurement of the currents due to ion transport immediately prior to breakdown. Using a technique involving a long time-constant, it appeared that there was a steady build-up of current in an irradiated gap, and a sudden build-up, at breakdown, in an unirradiated gap. A technique using a short-time-constant circuit revealed the fine structure of the current build-up as a series of pulses. A sensitive photomultiplier can pick up the emission of light from some of these pulse discharges, and we have recently been able to take simultaneous records of the current and light pulses.

Work of this type is now being planned for both uniform and non-uniform field breakdown, and at higher voltages. Uniform-field electrodes for working up to 1000kV are at present being made.

The influence of atmospheric humidity on the breakdown voltage of an air-gap is a matter of immediate importance to high-voltage engineers, but the data available are very limited. It seemed that the high consistency of the uniform-field gap made it a suitable means for detecting even such small changes in breakdown voltage as may be caused by variations in humidity, and a programme of research to this end has been in progress for some years. For gaps of the order of 1–2cm we have observed an increase in sparkover voltage with humidity for alternating, direct and impulse voltages. It remains to determine the possible contribution made to this effect by phenomena occurring at the electrode surface and in the air, and it is most desirable that the work should be carried to higher voltages, and include cases of divergent-field breakdown at voltages of practical interest. The present work is therefore to be regarded as introductory to work on a much larger scale.

The present situation is that we now have experimental techniques that exceed, by an order of magnitude, the sensitivity given by changes in breakdown voltage as an indication of a change in the breakdown mechanism of a spark-gap. Indeed, we have found it impossible to use some of these because of the slight variations that occur in the ambient atmosphere of the laboratories. It is also necessary to check the validity of theory over a wider range of atmospheric conditions than that afforded even by the Glasgow weather. For these reasons we are at present installing a controlled-atmosphere chamber some 9ft in height and 5ft in diameter in which it is hoped to work at up to 200–300kV in a stabilized atmosphere. Ancillary apparatus gives a pressure range of 0–2atm absolute, temperature control from −5°C to +30°C, and the full range of possible humidity values. Provision has been made for the application of dual photographic and other means of observation. In addition to providing more stable conditions for basic studies, it will be possible to produce conditions of icing, or low temperature and pressure, on such apparatus as insulators or on aircraft equipment.

Power Follow-Current Investigations

When flashover occurs on energized high-voltage equipment, a power arc will, in most cases but not all, be established in the path of the initial spark, and cause a short-circuit. The power follow-current carried by the arc has then to be interrupted. Work has been proceeding in the College for some years on the study of power arcs initiated by the impulse breakdown of a gap. A synthetic power source comprising a tuned *LC* circuit was first used with rod-gaps of up to 10cm and impulse voltages up to 200kV, as a result of which the various types of phenomena were classified and the important parameters identified. This synthetic power source can readily be modified, by altering the *LC* values, to give a range of frequencies and power source impedances. The impulse breakdown of the gap occurs under conditions simulating the application of a surge voltage at the instant when the power-system voltage is at a maximum, whether of like or opposite polarity to that of the surge. It was found that the critical condition for the development of a power arc was determined by arc-glow transitions which occurred at currents of the order of 1amp. Once the arc condition has been established, the short-circuit current that develops will be determined by the characteristics of the power source, but the critical condition is well within the range of laboratory equipment.

The investigation was then extended to include the effect of the point-on-wave at which the impulse was applied, using either high-voltage transformers as conventional power sources or the synthetic technique modified so that the voltage on the storage capacitor was varying at the instant of application of the impulse. Gaps ranging from 10cm to 15in were studied, and similar results were obtained with the two power sources. The most favourable condition for a power arc to develop occurs when the impulse is applied while the power-source voltage is still rising to its peak value.

Similar techniques could be developed for work on transformer insulation, and the synthetic circuit offers a means of producing a controlled amount of power follow-energy in the path of an impulse breakdown when testing transformers, so that the exact point of failure can subsequently be located.

Acknowledgments

I cannot name all the individual members of staff and research students who have contributed to the work described, but their names will be identified with the specialized papers that have been, or will be, published. I would, however, acknowledge the assistance received from the electrical industry in various ways, and from the Carnegie and Sir James Caird Trusts, and the Central Electricity Authority, in the award of research scholarships.

References

(1) Jones, F. L.: *British Journal of Applied Physics*, 1954, **5**, p. 49.
(2) Bruce, F. M.: *Journal of the British Institution of Radio Engineers*, 1951, **11**, p. 121.
(3) Bruce, F. M.: *Journal I.E.E.*, 1947, **94**, Part II, p. 138.
(4) Aked, A., Bruce, F. M., and Tedford, D. J.: *British Journal of Applied Physics*, 1955, **6**, p. 233.
(5) Dutton, J., Haydon, S. C., Jones, F. L., and Davidson, P. M.: *ibid.*, 1953, **4**, p. 170.
(6) Bruce, F. M.: *Endeavour*, 1954, **13**, p. 61.

Abstract No. 2331
Feb. 1957

SOUTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By C. J. O. GARRARD, M.Sc., Member.

'EDUCATION'

(ABSTRACT *of Address delivered at* BIRMINGHAM, 1*st October*, 1956.)

By its Royal Charter, The Institution is required 'to facilitate the exchange of information and ideas on Electrical Science and Engineering'. It is therefore one of our duties to concern ourselves with the education of electrical engineers and thus with technical education in general. There are four main fields in which this work is done, namely through our requirements for membership and the Institution Examination; through the Graduate and Student Sections; through the opportunities for further education provided by our ordinary meetings and discussions; and by advice given to Government, local authorities and other bodies concerned with education.

The Examination Regulations

The recent revision of the Examination Regulations has raised not a little the required standard, particularly in mathematics and physics, and has widened the syllabus in a number of subjects. It is to be hoped that, in applying the new standards in the schools and colleges, regard will be paid to the supreme importance of the elucidation of principles and the cultivation of the ability to learn from continued experience, as well as to the teaching of facts. Much difficulty in technical and scientific education might be avoided if more attention were given to what appear to be deficiencies in the elementary teaching of English and arithmetic—subjects which must continue to be the foundation of all more advanced studies.

The Institution, too, would do well to concern itself with the excessive specialization, not only in technological but also in humane studies, both in secondary schools and in universities. In electrical engineering courses, the growing unbalance between heavy- and light-current work is causing concern. The remedy in both cases appears to lie more in a general recasting of the course work than in mere additions to an already overloaded syllabus.

Graduate and Student Sections

The Graduate and Student Sections provide opportunities, not only for self-help by their 16 000 members, but for the senior members of The Institution to play their part in the education of the profession. It is essential that every opportunity be taken to cultivate that relation of pupil to teacher that is in danger of being lost, and of encouraging young engineers to acquire experience of responsibility at the earliest possible age; this in many cases may be more beneficial than continued academic training or post-graduate research. As a corollary to this we should encourage the provision of academic training for men who have already spent some time in industry.

If a man stays on to do research after taking his first degree, it is most desirable that the subject for investigation should be such that it can be grasped and carried through in a reasonable time by a single man or a group of two or three, who themselves can do the necessary thinking, planning and manipulation.

Meetings

The most striking development in the day-to-day work of The Institution is the continued increase in the number and diversity of its meetings, an increase to which the length of the year and the growing pressure of members' own work must presumably sooner or later set a limit.

The creation of Specialized Sections and Groups, while it has encouraged the multiplication of papers, symposia and conventions, has, by decentralization, provided to some extent at least the means for coping with the consequent greatly increased work of organization and has supplied the necessary audiences. The need to maintain adequate liaison between the resulting more or less different interests, however, lays upon the officers of The Institution a burden which, if it should be still more increased, may give rise to concern.

In organizing our meetings we should perhaps distinguish between two related but distinct functions of The Institution. One of these is to provide an exchange of information on the frontiers of electrical science. This it seems might best be done through *ad hoc* group meetings for the discussion by specialists of papers of more limited interest. At these meetings the papers could be taken as read, and the whole of the available time devoted to discussion, unless there appeared to be some advantage in an oral explanation of the subject.

The other function of The Institution is to give its members a general picture of the state of electrical engineering and to be a forum for the discussion of matters of general interest. Meetings for this purpose could often with advantage be based on lectures rather than papers; the lecture is often a more convenient means of summarizing and presenting a subject in a general way than is a formal paper.

At all our meetings, we should strive to increase the breadth and freedom of discussion by limiting the number of prearranged contributions, more strictly enforcing any necessary time limit on individual speakers and observing the existing rule against the reading of prepared statements.

Work outside The Institution

To-day almost all public discussion of technical and scientific education is concerned directly or indirectly with the shortage of scientists and engineers and with means to remove the shortage. The Institution is deeply concerned in these discussions, both in the persons of individual members and corporately.

At the personal level there are three things that might be said. The first is that there are grounds for thinking that the scarcity of technical staff is being aggravated to some extent by wrong and wasteful use of the people that are available. There is a great need for the application of work-study techniques to brain-work. Much time and time and trouble have been expended in applying time-and-motion study, methods development and similar techniques to the manual work of relatively plentiful and relatively unskilled workpeople. Some of this effort could well be diverted to studying the work of draughtsmen, designers and other technical workers.

Second, the fundamental difficulty seems to be a shortage of science teachers. If we want more we must see that the status of a teacher is at least as good as that of a doctor or a lawyer.

The third point is that if, as citizens or engineers or employers, we demand more and better scientific education we must not grumble when, as taxpayers, we are given the bill.

It is most essential that local authorities should be persuaded

Mr. Garrard is with The General Electric Co., Ltd.

to have the same liberality of outlook in their dealings with the colleges under their care as the University Grants Committee have in their dealings with the universities. The authorities should provide the money, see that it is not wasted, and beyond that interfere as little as possible in the affairs of the colleges.

Corporate action of The Institution will no doubt continue to be taken in supporting and improving the courses that are being set up for the recently instituted Diploma in Technology. One must agree that there is much force in the view that effective training can be carried out only in strongly staffed colleges offering a wide range of subjects; that a mediocre standard attracts only mediocre students and results in awards that are of little value. There is substance, however, in the view that the need is great and that help should be taken where it can be got.

The greatest need for many years will be for competent staff; here members of The Institution can help, either by part-time teaching themselves, or by making it as easy as possible for those of their staff who are willing to take up part-time teaching.

On a more formal basis, collaboration between industry and the colleges will be of the greatest value. An example is the sandwich courses now in being or being organized in many places. These are intended to supplement the existing university courses and to provide for those boys who do not get places in the universities a better engineering education than can be given by an apprenticeship with perhaps one day and an evening or two per week in college. It is felt, incidentally, that few boys will be able to cope with the new Institution Examination with only one day a week at college.

A sandwich course consists of periods of about six months spent alternately in the works and in the college for a total time of 5 years. The courses are designed to give the students a sufficiently thorough grounding in the basic disciplines of mathematics, physics, chemistry and so on, to enable them to think independently about their problems rather than merely to follow routine and rule of thumb. On the other hand, it is intended to give them, by the time they get into industry, some specialized competence and so enable them to establish themselves fairly rapidly as competent and authoritative engineers in the eyes, not only of their contemporaries, but also of men, sometimes their seniors, who have not had the same educational advantages.

While the active participation of industry in educational effort is wholly desirable, two possible tendencies should be kept in mind. One is that of diverting effort away from education, which should be directed towards the good of the individual and of the community in general and is the concern of private individuals and of the State, and towards training, which is properly directed towards the needs of a firm, a service or an industry, and should in the main be their responsibility.

The second tendency is that of accentuating the already grave shortage of good teachers and good administrators in the public sector of education by transferring many of the more capable people into industry. It might be supposed that the shortage of scientifically trained people would automatically set up conditions leading to an increase of supply. This unhappily does not seem to be true. In fact the shortage of technical men in industry is draining science teachers from the schools and thus creating an even greater potential shortage.

In education, as in many other things, one of our greatest needs is clearly to define and where necessary to delimit our objectives and then to concentrate upon their attainment a due portion of our scanty resources.

Even inside The Institution there may be some need for concentration of effort. We all welcome the steadily increasing bulk and intensity of its work. This is a sign of vitality, energy, public spirit and enthusiasm. One sometimes wonders, however, whether we are not approaching a time when we shall have to exercise some restraint in undertaking new commitments, especially in fields of a less essential character, in order that those that exist may be adequately discharged. While the work of The Institution is important and essential, our collective daily duties in the profession and the industry are even more important. In fact they are an irreplaceable foundation of the commerce and life of the nation.

We hear a great deal from time to time about education for leisure; there is doubtless need to teach people to spend their spare time more profitably, and leisure is necessary if the arts and graces of life are to develop at all. Nevertheless there is a danger that this propaganda may deflect us from what I think to be the truth, namely that we in this country are much less in danger from excessive leisure than from being obliged to work excessively hard.

If one looks at economic and technical developments at home and abroad, it is difficult to avoid the conclusion that in the not very distant future we are likely to have to work a good deal harder than we have in the past. More and more we are being turned back upon our own resources of materials and manpower. More and more our manufactures have to compete abroad with locally made goods and with the exports of countries which have a lower standard of living than ours; that is, whose inhabitants work harder and longer for less material reward than we do.

Added to all this is the fact that advances in medicine and hygiene are causing an explosive increase in the world's population, an increase at the moment of about one per second. This increase as it continues will exercise a pressure on food and other resources to which our children and grandchildren in these islands will be ever more exposed. The development of atomic energy, of automatic control and automatic production may give us some help. No one who has examined the question quantitatively, however, appears to think that the total effect will be much more than marginal for very many years.

We have to reckon with the possibility that the era of relative ease and prosperity through which we have been passing may prove to have been, not a prelude to even better things, but a passing phase. We should therefore be on safer ground, I think, if we tried to gear our education and related activities, such as those of this Institution, to preparation for harder work rather than for more leisure.

In so doing, however, we should not forget that the real need of the world is for fresh ideas. The fundamental notions upon which the whole of our scientific civilization is built are now quite old, some of them several thousand years old. We are involved in working out the ever-increasing mass of detailed consequence that has flowed from them. We are in fact in some danger of diverting effort from fundamental inquiry to short-range projects and of assuming that the only important aim of education is the production of material benefits.

No civilization can long survive unless it so orders its affairs that some at least of its citizens can pursue learning for its own sake, with open minds stimulated only by curiosity. Experience has shown during all the ages that it is such men and they alone who achieve the epoch-making discoveries that ensure future progress.

Abstract No. 2300
Feb. 1957

SOUTHERN CENTRE: CHAIRMAN'S ADDRESS

By H. ROBSON, B.Sc., Member.

'MANAGEMENT—THE PROSPECT BEFORE US'

(ABSTRACT *of Address delivered at* PORTSMOUTH, *3rd October*, 1956)

Management itself is usually regarded as an attractive subject and has a wide appeal; because of this there is the impression that the subject is a peculiarly easy one, but as we shall see, this is an erroneous impression. In a well-managed place it all looks so easy that one never realizes that perspicacity, hard work and integrity are all there in the highest degree and at all levels. It is, in fact, under modern conditions of working, a very complex subject.

Professor Moullin, in his Inaugural Address, has drawn attention to the centralization of administration to the exclusion of the ideals of the professions, and Lord Citrine has blamed engineers for not equipping themselves for management.

An outstanding feature in the history of our country's industry during the last quarter of a century has been the trend towards centralized administration. Another feature has been the extent to which, in their early stages at any rate, the organizations follow a pattern.

In the initial or formulatory periods of these organizations, management is characterized by direct control from headquarters through specialist functional control. There is a tendency on the part of headquarters to disregard local interests in the interests of uniform administration and to concentrate all its powers centrally, but it is not always in the best interests that this should continue. In this change of outlook, a manager's attitude must also change, while from a legal point of view, deriving his authority from a single source, he is not in a position to ignore certain other influences. There are, I think, six sources in all to be considered in this connection.

First there are policy directives and instructions from the body exercising overall control, but a system of management based on administration alone would become too rigid to work. Secondly there is legislation, and regulations authorized by legislation; all parties have a right to expect that men in charge should observe Acts of Parliament without having their attention specifically directed towards them. Then there is negotiating machinery. Although national bodies are responsible for the determination of terms and conditions of employment, local machinery exists which is primarily concerned with securing the observance of such terms and conditions and dealing with any local difficulties or differences that may arise. In addition there are advisory committees, local traditions, practices and conventions, and consumer demands.

These sources of authority, you will observe, fall into two groups. The first three have little local significance; the other three are entirely local in their derivation, and their sanction is merely conventional in character, that is to say there is no written authority for its existence, but it is real, nevertheless. It must be remembered that in the political world many of the most effective rules of constitutional government possess merely a conventional character. During the formulatory period of an organization's existence the influence of advisory committees, local traditions and consumer demands must, in the interests of expediency, become subsidiary considerations and may for a time be ignored, but they cannot permanently be repressed.

It is worth repeating an old tag—that management is a form of government which can only succeed if everybody connected with it observes the 'rule of law'. Just as we have the traditional separation of powers of government into legislative, executive and judiciary, so in industry we have a tripartite separation of powers, and we speak of overall control, operational management and functional management. A very brief description of each of these terms is all that is required for our purpose:

Overall Control.—This is usually exercised by a group such as a board of directors, a committee of a local authority, or the members of a public authority appointed by a Government minister. Like the Government, they accept collective responsibility and are responsible for making policy but do not, as a body, concern themselves with day-to-day management.

Operational Management.—This is the job of putting into effect the policy made by the controlling body and is concerned with the main activity of the business. It differs from *functional management* in this respect, that it has to relate policy decisions and executive actions and at the same time preserve a balance between all sections of the business. Functional management, being a more specialized activity, only concerns itself with the efficiency of a particular part of the business. Examples are design, purchasing, costing and advertising—unless these are the main activity of the business. The boundaries of operational and functional management need not be contiguous. Whereas the size of an operational management unit is determined by the size of the group for which a manager can take personal responsibility, functional management, being narrower in scope, may cover a number of operational units. An example of this is a purchasing department. Usually one department, centred at headquarters, can deal with all purchasing matters without having outposts.

It is just as essential in industry as it is in political government, for the efficient operation of an undertaking, that this separation of powers should be maintained as far as possible and that there should be safeguards. These are provided in three elements we have mentioned, namely advisory committees, local traditions and consumer demands.

While most people will agree with the conception, some people have doubts about the practicability of it. These latter people, for instance, find it difficult to reconcile the requirements of the 1947 Electricity Supply Act, which calls for standardization of tariffs, systems of supply and types of electrical fittings, and for economies which can result from large-scale organization, with the urge to achieve flexibility, which it is claimed is necessary to make the organization workable. They feel that standardization can only be achieved centrally; that flexibility can only be achieved locally; and that the two things are therefore incompatible. I think that for an answer we might well turn to the modern scientist.

The main faith of the scientist is that there is an order of nature. Although year follows year, season follows season, and night follows day with certainty and precision, yet no two years, no two seasons, no two days are the same, and nothing we can do will make them the same. Nor are they capable of precise prediction. Even so, the scientist believes that every event, every happening, is related to the laws of nature. Similarly with management, while no two units are the same, no two employees are the same, no two situations are the same, there is no reason why actions taken locally to meet the law of the situation should not conform to a general policy and at the same time be effective.

It is often thought that centralization of authority and of control are modern conceptions, but I should like to remind you that for the beginnings of centralization of the administration of

* Mr. Robson is with the Southern Electricity Board (Portsmouth District).

justice you have to turn back to the 12th century, and a brief examination of its development is useful to show that many of the problems we are facing to-day have, in form if not in detail, been faced and overcome in other spheres of government many years ago. There has been a system of justice in England from very early times. Originally it was administered in rough and ready fashion, then under some control in local seigniorial and communal courts, and finally in the King's Courts.

The characteristic feature of this system was its precision and the exact predetermined penalty fixed for each offence, which was applied irrespective of the circumstances surrounding the case. Because of this rigidity of application of penalties it became the practice to seek relief from the harshness of the system by petitioning the King for justice in default of justice in the Courts. By justice was meant, in this context, not necessarily the verdict which conformed to the rules of the system of law administered in the courts, but justice in the abstract, or equity.

The weakness of the procedure was that the hardship had to be created before the remedy could be applied for, and this unhappy state of affairs existed until it was realized that both the law and equity had to exist together, and since the passing of the Judicature Act in 1873 the rules of both systems are recognized in all courts and are administered by the same judge. The result is a flexible and workable system where once there was rigidity and friction.

So having centralized to achieve a common law, and having produced a system which was too rigid to work successfully, we come back to a modified local jurisdiction with control from above which gives it the quality of consistency which was originally aimed at, but not originally achieved.

I do not apologize for dipping into the past. I believe that the habit of looking only into the future is characteristic of adolescence and is the principal cause of irresponsible actions; in order to understand the future we must understand the mistakes of the past.

The extent of background knowledge and the ability to profit from it is the factor which distinguishes one manager from another. Each man's background differs, but there are some basic factors which are common to all and which endure through the diverse strata of industrial organization.

First there is the knowledge required to deal with difficult situations as they arise. But it is much more important and proficient to prevent them happening at all. It has been said that Virgil's Latin is the art of making two or three words, chosen to go together, have far more meaning than the total of the meanings of the individual words. In the same way a good manager can achieve in a team of men something far greater than the sum of their individual capacities.,

Secondly there is the knowledge, where men are concerned, that attempts at rapid or premature action are apt to provoke a reaction which defeats their aim. As a rule young people think that a manager acts too slowly; the older ones are apt to think he acts too precipitously; quite often they are both wrong because neither of them know all the facts.

Thirdly there is the appreciation of balance, sometimes referred to as a sense of proportion. Balance is one of the classical virtues. It implies an equilibrium of *all* forces in action.

Fourthly there is the skill in meeting difficult situations and in dealing with difficult people. Many good causes have been lost for want of skill in introducing and handling them. It is not sufficient to have a good reason for doing a thing. You have got to get other people to accept it as a good reason and you have to know how to make them accept it. Sir Arthur Quiller-Couch says that writing, to be good, must be persuasive: so must management.

Fifthly there is the knowledge that to get at the root of any trouble one has to get at the truth, that is the absolute truth and not what people think to be the truth. This is no easy matter, although we all believe we can recognize the truth when we see it.

Sixthly there is persistency. All men who have achieved a measure of success have shown this quality. It is reported that Newton was asked how he came to formulate his theory of gravitation, and he replied, 'By always thinking about it'.

Seventhly there is consistency. People below and above the manager have a right to expect consistency of him. In this way he is trusted to do the right thing when the occasion arises without quibble or question.

We have to safeguard against administration becoming an end in itself. The safeguard appears to be this: that managers should be recruited from men with a sound training in the basic activity of the business. Such men are able to focus on performance and to establish objectives and yardsticks, and are therefore better able than others to see the business as a whole. But the suggestion has been made that men with technical training are no longer interesting themselves in what might be called the 'humanities of industry', which we have seen to be among the essential ingredients of management, and are therefore unable to see the business as a whole. This is because some of them find undistractible absorption in technical details; others of them believe that many of the factors and influences we have just examined tend to reduce management to what Sir Harold Nicolson has described as 'such thin virtues as precision, tidiness, formalism and conformity'.

Intense specialization is narrowing the outlook of technical minds in its demand for exactness; making them blind to matters which require a wider approach. The correcting factor must surely be a combination of technical knowledge with general knowledge and humanistic traditions.

Management, like sundry other arts and sciences, is, at the present time, in the melting pot. I have attempted to show, and I trust I have left you with the conviction, that management is not a science to be studied but an art to be practised—and practised successfully under all conditions. Theory seems in general to have outridden practice. There never was a time when more was said and written *about* management. But are we not reversing the order of things when we expect theory, however brilliant, not only to precede practice but to determine its course?

Abstract No. 2271
Feb. 1957

NORTH LANCASHIRE SUB-CENTRE: CHAIRMAN'S ADDRESS

By E. H. SCHOLES, Associate Member.

'POST-WAR DEVELOPMENTS AND TRENDS IN GENERATION AND TRANSMISSION'

(ABSTRACT *of Address delivered at* PRESTON, 10*th October*, 1956.)

Conventional Generating Plant.—It is perhaps difficult at the present time to appreciate that, at the beginning of the century, power stations of 1 000 kW were exceptional, and that now stations of over one million kilowatts are accepted as normal practice.

The extreme shortage of generating plant during and since the last war resulted in standardization on 30 and 60 MW units in order to speed up the manufacture and construction of new generating stations. When this problem had been basically resolved there were three main factors which influenced the design of steam generating plant, namely the urgent need for fuel economy; the necessity to keep capital and operational costs to a minimum; and the requirement that all new plant had to be capable of either single- or two-shift operation.

The rapid improvement in boiler availability, due in no small way to the work of the Boiler Availability Committee, led naturally to the conception of the unit system—one boiler, one turbine—without interconnections on the steam side. In 1946 about 20% of the coal used in power stations was burnt in pulverized-fuel boilers; the figure is now 50% and still continues to rise rapidly.

The decision to adopt the unit system led to a reconsideration of the reheat cycle in order to effect greater economies. This factor, coupled with the need to rationalize blade sizes and profiles, led to the development of larger generating units from 60 MW to 100 MW and more recently to 200 MW. Still larger sizes are being planned to operate at even higher pressures, and the fact that all such plant must be capable of either two- or single-shift operation appears to be the main limiting factor.

Nuclear Power.—The urgent need to augment our inadequate supplies of coal has undoubtedly been one of the main contributory factors in the rapid development of the Government's nuclear power programme. Assuming that a maximum allocation of 60 million tons of home-produced coal for electricity generation will be reached in 1970, it is estimated that this will meet less than half the country's needs by 1980. The balance can therefore only be met by either imported fossil fuels or nuclear power. Limited operating experience precludes the preparation of accurate costs for construction and operation, but present estimates are considered to be reliable enough to show that nuclear power plants should be competitive with modern conventional plants. The unavoidable high capital costs of the former will result, however, in such stations having to operate at optimum load factor.

The fact that nuclear physics in 1939 was as remote from practical application as was electromagnetism a century ago gives some indication of its rapid development during recent years.

The adoption of graphite-moderated gas-cooled reactors to cover the requirements of the first 20 years' programme would appear to be justified if the strain on our national fuel resources is to be relieved.

The need to obtain suitable ground to support the heavy loads remote from built-up areas, coupled with the large quantities of cooling water required, has and is creating difficulty in choosing suitable sites.

Pumped Storage.—The urgent need to increase the night load and so to improve the system load factor, coupled with the advantage of having large blocks of immediate standby potential energy available at all times, has made the case for pumped storage very attractive. The value of such schemes will be greatly enhanced in order to meet the requirements of the nuclear power programme when it is anticipated that ultimately surplus supplies of cheap electricity will be available for pumping purposes during the night and at week-ends. The merits of the pumped storage system are therefore even more obvious where there is a wide difference between the cost of generation of the peak-load plant and the base-load plant.

Although there have been quite a number of such schemes in operation for many years both on the Continent and also in Canada and the United States, the first major scheme in this country is now under construction at Blaenau Ffestiniog in North Wales. The total plant capacity of this station will probably be 300 MW, i.e. six 50 MW units. The operational costs should not exceed 60% of the present peak-load generation costs, and the capital costs will be lower than those of the equivalent thermal station. There is, however, a limit to the number of suitable sites available in the United Kingdom for this purpose, and a recent uncompleted survey envisaged a potential capacity of 2 000 MW.

Transmission System.—The existing 132 kV system was constructed by the Central Electricity Board in the early 1930's following the 1926 Electricity Act. Prior to that date each undertaking had to install sufficient generating plant to ensure security of supplies to its own consumers. Due consideration had also to be given to the possibility of actual demands exceeding estimates.

The 132 kV system was designed specifically to pool the spare generating plant in limited areas, and in this way very large savings in plant capacity were made. It was not, however, until 1938 that all the seven areas were coupled together to form a national system.

Since that date the national demand has increased so rapidly that the 132 kV system is now totally inadequate to deal with the large inter-area transfers which are required to run the whole of the plant in the country in the most economical manner.

After careful investigation it was proved conclusively that the only practical way of overcoming this problem was to construct a new superimposed Grid to operate at a higher voltage. The highest practical voltage which could be considered at the time was 275 kV. It now seems obvious that the original scheme will have to be reinforced in order to meet the accelerated nuclear power programme.

If full advantage is to be taken of all the developments which I have already mentioned, it is important that more attention should be given to the improvement of our system load factor as a whole. This problem will become even more acute with the advent of nuclear power.

Mr. Scholes is with the Central Electricity Authority (North West, Merseyside and North Wales Division).

Abstract No. 2304
Feb. 1957

RUGBY SUB-CENTRE: CHAIRMAN'S ADDRESS

By J. H. CANSDALE, Member.

'POWER FOR TRACTION'

(ABSTRACT *of Address delivered at* RUGBY, *9th October*, 1956.)

The introduction of mechanical transport for road and rail vehicles has taken place almost entirely within the last 150 years, and there has been a rapid development of various forms of motive power other than steam within the last 50 years. The internal-combustion engine now dominates the roads, though electric vehicles still have an important part to play in public transport. On the railways, steam is at length giving place to electric and Diesel-electric power, and the future of railways largely depends upon their ability to modernize their systems to meet the severe competition from road vehicles. The bold modernization scheme of British Railways is an example of wise planning to meet a difficult situation.

With various types of motive power available, both on road and rail, the problem is to know which to select for any particular job. Some of the factors to be considered are as follows.

Fuel

A century ago, coal was the principal source of energy, but to-day it supplies only about 50% of the total power used in the world. Oil consumption has increased eightfold since 1920 and is expected to double over the next 10 years. Both oil and coal are, however, irreplaceable natural assets and must eventually be exhausted. Furthermore, the supply of oil to the British Isles is subject to the uncertainties of international politics, and recent events in the Middle East have made this all too obvious. Fortunately the development of nuclear power stations gives a promise of supplies of electric power which will be independent of coal and oil, and this must be taken into account when planning for the transport of the future.

Comparing the overall fuel efficiency (i.e. the ratio of primary fuel energy to work output) of the steam locomotive at 7–8%, the electric locomotive at 13–14% and the Diesel-electric locomotive at 28–30%, the latter appears to have a great advantage over the two others. But when the higher cost of oil, together with the uncertainty of its supply, is taken into account, the electric locomotive shows up to great advantage in overall economy. The same is true of battery-electric vans and trolley-buses when compared with petrol vans and Diesel buses. Operating on comparable types of service, the cost of electric power used is less than that of petrol or oil.

Speed and Acceleration

In all forms of transport the overall or schedule speed over a journey can be shown to be of much greater importance than the maximum speed which the vehicle can attain. The battery-electric van, with a top speed of 18–20 m.p.h. can show a better overall performance on door-to-door delivery work than a petrol van which has a top speed more than twice as great. This also applies to the trolleybus, which can show an advantage in schedule speed over a Diesel bus on any service of 6 or more stops per mile.

On any rail service with short distances between stops, as on city or suburban electric railways, a high rate of acceleration becomes of supreme importance. It is for this reason that such services are invariably operated with multiple-unit stock, which can maintain a high rate of acceleration regardless of the train make-up.

Sustained high speed does become important for main-line trains, and the latest locomotives proposed for British Railways will have a balancing speed of 90 m.p.h. and a maximum safe speed of 100 m.p.h.

The serious reduction in schedule speed of road traffic due to street congestion is one of the great problems of to-day. It has recently been stated that the speed of traffic in London at peak hours is no better than in the days of the horse bus. The private motor-car is held to be largely responsible for this state of affairs, and the solution for large cities appears to be the provision of car parks at suburban stations and speedy electric passenger services on reserved or underground tracks into the city centre.

Weights and Gradients

The importance of a good ratio of pay load to gross weight is now widely appreciated, and great efforts are being made to reduce tare weights. A modern lorry with light-weight body construction has a pay load of 75% of the total weight, which may be compared with a goods train figure of about 55%. Improvement in road public-service vehicles during the past few years has reduced the tare weight per passenger from over 300 lb to just over 200 lb. This has enabled the number of seats to be correspondingly increased. Rail passenger-coach weights are also being drastically reduced, and designs are being tried out with a tare weight per seat of between 4·5 and 6·5 cwt; these may be compared with tare weights of 10–18 cwt at present in use in Britain and America.

The effect of even small gradients on the power required is of very great importance. For example, a goods train moving at slow speed on a 1 in 600 gradient requires about double the power necessary to move it at the same speed on the level.

Adhesion

Adhesion constitutes a major limitation with all railed vehicles, but this is an inevitable accompaniment of the low tractive resistance of steel tyres on steel rails. Research has shown that the phenomenon of adhesion is still only partially understood. Experiments with certain chemicals sprayed on to the rails have shown that better results can be obtained in this way than with sand, and it is hoped to obtain improved control of wheel slip by this means.

The rectifier locomotive has been shown to have better adhesion characteristics than the corresponding d.c. locomotive, and very high adhesion factors, up to 46%, have been claimed during tests on the French Railways. Their latest locomotives are being designed for an adhesion factor of up to 40%. This is one of the reasons for the choice of 25 kV 50 c/s a.c. power for future electrification in Great Britain, since it permits the use of a 4-axle locomotive in some cases where a 6-axle d.c. locomotive would be required.

Wages

The importance of wages can easily be overlooked when considering purely technical factors. From one-half to two-

Mr. Cansdale is with the British Thomson-Houston Co., Ltd.

thirds of the cost of transport is due to wages, and a reduction in labour costs may be of greater significance than a technical improvement. The use of one-man buses for road transport and Diesel cars on the railways enables one man in each case to be dispensed with, and this effects an important saving in labour costs.

Intangible Factors

In addition to the above factors, which lend themselves to statistical treatment, there are other intangible factors, whose value can seldom be expressed in figures. Comfort, convenience and cleanliness are accompaniments of electric traction of all kinds, but their value can never be properly assessed. The use of home-produced power which is free from the uncertainties of supply from oversea is a very important advantage, but this again cannot be shown in actual figures. Cleanliness and absence of fumes are matters of great importance to public health, but they are too often overlooked completely when consideration is being given to the best type of vehicle to use.

Electric vehicles are usually limited to routes equipped with overhead or conductor-rail supply, and this is held to be a disadvantage, though it is seldom now necessary to change a route once it is laid down. The gyrobus, which uses the energy stored in a flywheel to operate between recharging points several miles apart, is a type of electric vehicle which does not need any overhead wire. It is of limited application at present for road vehicles but seems to have possibilities for application to small shunting and mining locomotives.

The trend in transport is definitely towards electric power. The railways are already making moves in that direction, whilst recent difficulties with oil supplies show the folly of leaving public transport vehicles to be entirely dependent upon oil. Electric power is the power of the future, and wise planning for future transport, whether on road or rail, will take this fully into account.

Abstract No. 2303
Feb. 1957

SHEFFIELD SUB-CENTRE: CHAIRMAN'S ADDRESS

By G. G. NICHOLSON, M.Eng., Member.

'ELECTRICAL DEVELOPMENTS IN THE PRODUCTION OF SHEET STEEL'

(ABSTRACT *of Address delivered at* SHEFFIELD, 17*th October*, 1956.)

Sheet-steel and tinplate production in this country represents about 15% of the total steel production, and last year the total quantity of sheet and tinplate produced was over 3 million tons. Sheet is used for the production of automobile bodies, refrigerators, washing machines, etc., and tinplate is used for containers for food, tobacco, etc. Sheet steel was first produced by the semi-continuous process in 1926 and has developed until there are now about 30 hot strip mills in the United States and three in this country.

The process of producing strip steel consists in reducing an ingot of steel which may weigh up to 20 tons into a slab on a reversing slabbing mill. After reheating, the slab is passed through a hot strip mill and then after pickling to remove scale is further rolled in a cold mill to produce cold-rolled strip. This is then annealed and temper rolled to give the correct grain structure for deep drawing.

The reversing slabbing mill is driven by two direct-coupled d.c. motors, usually of 4000–6000 h.p. with a normal base speed of 40 r.p.m. These machines are supplied from a Ward Leonard Ilgner motor-generator set, and rotary quick-acting exciters are used to force the generator and motor fields to give quick response; in addition, separate quick-acting exciters are used to balance the load between the two mill motors.

The latest development in slabbing-mill drives is the supply of power to the main driving motors by single-unit rectifiers with armature reversal by quick-acting contactors. The circuits are arranged so that the contactors do not have to break motor current, and the rectifier is so controlled that the change-over from rectifier action to inverter action occurs in a controlled manner. The development of the rectifier scheme has reached the point where the main mill motor can be reversed in approximately 1·5 sec, which is equal to that achieved with normal generator control. The rectifier scheme has a lower capital cost and higher efficiency, but suffers from the disadvantages of lower power factor and the fact that the full peak power must be supplied from the h.t. system.

In the finishing trains of hot strip mills the steel is in all stands at the same time, and these stands are all driven by d.c. variable-speed motors supplied from mercury-arc rectifiers. Grid control of the rectifiers is used for accelerating the mill, for inching purposes and for full voltage regulation when running. It is normal to arrange the rectifier units in groups with phase-shifting transformers to give the effect of multi-phase rectification, so avoiding the effect of harmonics.

The type of cold mill used will depend on the ultimate thickness of strip required and the desired output. For high outputs a tandem mill is used and the number of stands is determined by the finished gauge, a 5-stand mill being used for the tinplate gauges and a 3-stand mill for the heavier sheet gauges. The economic speed for each type of mill is determined by coil lengths, and speeds of 2000 ft/min for a 3-stand mill and 5000 ft/min for a 5-stand mill are now common. The total motor power may be up to 20000 h.p. for a 5-stand mill. It is essential that the speed relationship between stands is maintained during acceleration, running and deceleration. Each stand motor may be of the multi-armature type to reduce inertia, and is supplied from its own generator. Quick-acting exciters are used to maintain the speed relationship between stands at all speeds. After the strip has been rolled it is coiled on a reel under constant tension. This is achieved by maintaining the reel-motor current constant by a servo system and adjusting the reel-motor field by a servo control to keep the reel-motor voltage proportional to the speed of the strip.

After rolling tinplate it is necessary to remove the rolling lubricant before annealing to avoid tinning difficulties. The lubricant is removed by scrubbing in a detergent solution combined with an electrolytic action. One new plant in this country will have an electrolytic section fed from two germanium rectifiers each rated at 18 volts, 7500 amps; this is one of the first heavy-current applications of germanium rectifiers in this country.

The developments in high-speed rolling combined with rapid acceleration and automatic tension control have been aided, in no small measure, by the post-war development of quick-acting exciters. They are now being superseded to some extent by the magnetic amplifier, which has no moving parts and requires very little maintenance.

Mr. Nicholson is with the Davy and United Engineering Co., Ltd.

A new development is the use of radioactive isotopes for the measurement of thickness by β- and γ-rays. These are challenging the established X-ray gauge, which has been used for some time for this purpose. Developments are proceeding in automatic gauge control on strip mills both here and in America, and a number of production mills are now running with this type of control.

A recent introduction on hot strip mills is the strip-width meter, in which accurate measurement is carried out by the use of photocells and scanning devices mounted above the roller table carrying the moving strip. By this device the width can be measured even though the strip is wandering on the table.

Pinhole detectors are used for the detection of minute holes in strip of tinplate gauge before and after the tinning process, and any strip containing holes is automatically rejected by a solenoid-operated classifier mechanism.

A number of electrolytic tinning lines have now been installed; in these the coil of untinned steel is unwound, cleaned, tinplated, heated to melt the tin to obtain a shiny surface, and then cut automatically to length—all in one continuous automatic operation.

The phenomenal increase in mill speeds and outputs since 1945 has been brought about largely by improvements in rolling techniques and the great advances in the art of electrical engineering.

Abstract No. 2305
Feb. 1957

NORTH SCOTLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By R. B. ANDERSON, Member.

(ABSTRACT *of Address delivered at* ABERDEEN, 7*th November, and* DUNDEE, 8*th November*, 1956.)

Progress

Up to the end of 1955, that is in about 13 years, the Hydro-Electric Board have added 474 MW of hydro-electric generating plant to the 85 MW previously operated by the Grampian Company. Twenty-two post-war plants have been commissioned, and a further 18 were in hand at the end of 1955. These are calculated to provide a further 310 MW and 952 million kWh per annum. The growth of load in the Area is roughly equal to the output of a new 30 MW generating plant each year. Over 110 miles of rock tunnel have been driven in connection with these projects.

At the end of 1955 the capital expended during this 13-year period amounted to £140·5 million—67% on hydro-electric schemes and about 30% on transmission and distribution. The Scottish Centre Chairman, in his Address in 1954, stated that the cost per consumer in Central Scotland had increased from £65 in 1948 to £113 in 1952. According to the Hydro-Electric Board's figures, their corresponding average cost in 1952 was £165 per consumer and this is again up in 1955 to £262.

The probability of relatively high average costs was referred to in the Cooper Report, and this difficulty has, of course, become progressively worse due to the trend of world prices. Nevertheless, 16 000 new consumers were connected last year, making a total of nearly 150 000 since the Hydro-Electric Board started their operations, and in the most northerly and sparsely populated counties on the mainland nearly 90% of the premises now have a supply of electricity.

By the end of 1955 there were almost 1 300 circuit-miles of 132 kV overhead lines in operation, the highest being 2 507 ft above sea level in the Corrieyairack Pass in Inverness-shire, and the most northerly terminating at Mybster near John o' Groats—about the same latitude as Moscow.

The development of any rural area inevitably involves the use of a large number of transformers. H.V. distributors are run as near as possible to farms and crofts, and small transformers are used to serve groups of consumers, by short l.v. service lines. The number of transformers averages at about one for every 10 consumers. The annual costs of the losses present a formidable burden; for example, losses associated with a 25 kVA single-phase unit will amount to over £11 per annum, whilst a 5 kVA unit will account for £3 per annum for iron and copper losses alone, and when other capital charges are added, a large proportion of the total revenue is absorbed.

Mr. Anderson is with the North of Scotland Hydro-Electric Board (Dundee Area).

Development

It would appear that the consumption of electricity by the typical rural domestic consumer in the north has been increasing just about twice as rapidly as that of the domestic consumer in the city. In industry the increase is impressive; the energy used per worker in a typical city industrial area has increased by over 80% during the past six years.

In agriculture, larger farms are using substantially more units, but the effect of connecting relatively large numbers of small farms and crofts results in the average per consumer being lower in this category.

If the demand continues to do no more than double itself over six or seven years, the problem of providing adequate resources in the large towns and cities will become increasingly formidable.

The highest-voltage circuits tend to become, in fact, distributors. At the same time, short-circuit values on the lower-voltage systems and on consumers' premises must be kept down to reasonable proportions.

The necessity for expansion is apparent in urban and country areas also, and it would appear that villages with a population of over 1 500 will, in the future, require to be dealt with by underground cables, in the main streets at least.

Distribution Lines

In the north, as elsewhere, cost comparisons have promoted the tendency for aluminium conductor in some of its forms to supplant copper. This has produced somewhat variable results, both operationally and economically; nevertheless, it would appear that the supply position will lead to continuation of this development, not only for overhead lines but for underground distribution also.

Switchgear

Whilst all possible economies must be made in dealing with the sparsely populated areas, the community, nevertheless, rely on a high factor of continuity. A useful contribution towards this is the provision of auto-reclose or automatic change-over equipment on important switchgear, and there seems every incentive to expansion of this policy in the future.

The Americans claim that improvements in continuity, economy and simplification resulted from the adoption of reclosers in conjunction with fuses, and at first sight it may seem surprising that this system has not made more progress here. There are, however, few 11 kV distributors in these parts which

are sufficiently long or have a sufficient number of important spurs to justify adoption of this system. There may, however, be variations which are worth investigating. It would not be difficult to apply the principle of instantaneous tripping to existing switchgear, and one fairly quick reclose could be followed by delayed tripping.

Further development of the use of medium or slow-acting fuses would itself seem worth while. More use might be made of the thermal characteristics of transformers, etc., to make available longer discrimination times. Indeed, it does not seem unreasonable to suggest that supply authorities might in time standardize on such fuses, leaving the present 'fast-acting' types in the consumer's province, and this principle might apply equally to l.v. circuits. The difficulty is, of course, that the slower-acting fuse is bound to have a lower rupturing capacity. The problem of getting rid of the heat is a serious one, but possibly, in time, manufacturers may find a way round some of these difficulties.

Abstract No. 2286
Feb. 1957

SOUTH-EAST SCOTLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By F. G. BENNETT, M.I.Mech.E., Member.

'THE ELECTRICAL INSTALLATION ENGINEER'

(ABSTRACT *of Address delivered at* EDINBURGH, *16th October*, 1956.)

In the *Journal* for June, 1956, the editorial dealt with 'Electrical Installations and the Professional Engineer'. The Address commences by quoting the opening lines, which state that there is a tendency to assume that professional engineers are not necessary to electrical installation work and that such experience is not necessarily sufficient to satisfy the requirements of Bye-Law 12. The generally accepted definition of a professional engineer is quoted, to which two other requirements are added—flexibility of mind and soundness of judgment.

To give clarification, therefore, the Address deals with some of the responsibilities of the installation engineer and the essential features of his organization. Emphasis is laid on the engineering and allied facets.

The scope of activity of the individual contractor may range from electronic aids to heavy industry and embrace repairs of electrical equipment, rewinding of rotating plant and maintenance work. There are many factors which determine the extent to which a particular organization participates in these activities, not least being the degree of specialization favoured by the management and the finances available.

The work derives from many sources, but basically it may be classified into three groups, namely (i) from a scheme prepared by or on behalf of the user, (ii) from a scheme submitted by the contractor in competition with other freewill schemes, (iii) from a direct instruction to report on, and thereafter prosecute, a project. Those organizations employing chartered and qualified engineers tend towards groups (ii) and (iii). The technical resources, however, must be complemented by satisfactory estimators, labour supervisors, progress engineers, costing and invoicing systems, stores and general clerical staff, together with adequate workshop facilities.

The planning of an installation is confined by statutory enactments or specialized codes, or both. These are briefly discussed: they include the Electricity Supply Regulations, Electricity Regulations, Factories Act, Coal Mines Act, Quarries General Regulations, Metalliferous Mines General Regulations, special Statutory Instruments for cinemas, dangerous and unhealthy industries, etc., The Institution's Regulations for the Electrical Equipment of Buildings, specialized requirements of consulting engineers and larger users, British Standards, including special handbooks and Codes of Practice, Codes of the Illuminating Engineering Society and insurance companies, and finally the Building (Safety, Health and Welfare) Regulations.

The approach to each scheme must co-ordinate the technical requirements, financial obligations and practical difficulties to the user's satisfaction. A brief review of the work involved is included and is emphasized by outlining the factors to be considered in the conversion of a factory to electrical drive. These include existing loads and running costs, substation equipment, methods of power-factor correction, understanding of speed/torque and load/time characteristics for motor applications, lighting and heating schemes, types of distribution equipment, rupturing capacity, system stability, mechanical features and millwrighting. Private generation and the need to understand the limiting features of the various prime movers are mentioned.

The necessity to present clear and embracing reports is emphasized, and the factors to be included are outlined.

Some of the additional aspects of the chartered installation engineer's activities are quoted, such as advisory work for builders, architects, surveyors, insurance assessors, local and national committees, etc.

To augment the purely technical resources, there are a number of functions demanding technical ability in varying degrees. First there is the drawing office to prepare diagrams and working drawings, 'as fitted' drawings, detail drawings of such equipment as switchboards, mechanical fixtures and drives, surveying of buildings and machinery, layouts of substations, plant houses, cable runways, foundations and the like. Secondly, almost all contracts have to be quoted. The essential need of estimators is to be able to put an accurate cost on labour and material which can only be done from experience and an intelligent appraisal of the site conditions. Given adequate supervision, the financial success of the contractor depends initially upon correct estimating. Thirdly, supervisors are required to control labour, plan work on site, interpret contract conditions, co-ordinate material and labour to a programme, test and commission, and finally remeasure work at completion for invoicing. Proper supervision pays dividends. Fourthly, there is the workshop, with which is associated repairs, rewinding, maintenance work and the manufacture and assembly of switchboards, control panels, busbar systems and trunking as typical electrical examples, and general engineering work on the mechanical side.

In support of the technical aspects, a flexible commercial structure is necessary, consisting of secretarial staff, accounting, invoicing, costing, sales records, purchasing and storekeeping. Of these, costing and purchasing with stock control are of particular importance in to-day's difficult trading conditions.

Brief mention is made of craftsmen and apprentices and the training of boys.

The controversial aspects of commercial policy are noted, and reference is made to the Fair Trading Policy, the National Inspec-

Mr. Bennett is with Wm. Allan Smith and Co., Ltd.

tion Council, State trading and competition from certain manufacturers. Brief allusions are made to social and welfare work, human relations and other issues supporting the salient feature of technical ability.

The primary concern of the Address is to demonstrate that professional engineers have a definite place in the planning and carrying out of installation work. It is reiterated that, additional to his technical duties, the contractor must have a reasonably intimate knowledge and experience of labour relations to ensure that the work is carried out satisfactorily, of costing and accounting methods to result in financial stability, of the commercial implications of contractual obligations, insurances and legal matters to promote operational integrity.

Satisfaction is expressed that the Council's endeavour is to make a true appraisal and to correct misapprehensions. The Address ends by quoting the conclusion of the editorial mentioned in the opening remarks: 'The importance of installation work and its professional nature are reaffirmed, for these aspects have certainly not receded through the widespread developments of electrical science and engineering.'

Abstract No. 2319
Feb. 1957

SOUTH-WEST SCOTLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By J. W. MACFARLANE, Ph.D., Wh.Sc., J.P., Member.

'PERSONAL EXPERIENCES WITH HEAT PUMPS'

(ABSTRACT *of Address delivered at* GLASGOW, 16*th October*, 1956.)

In September, 1945, whilst in Germany I met the late Dr. S. Whitehead, who casually mentioned that he had recently been to see a heat pump installed in a German submarine. Having never heard of a heat pump, I made a note that evening, and some months later I looked up heat pumps in general. It immediately struck one of my ancestry that here was a possibility of obtaining something for nothing. Any device with an efficiency, which, on the face of it, was greater than unity was certainly something I should know about.

Now, past my old house there runs the White Cart Water. The house is on a rock some 90 ft above it, and I thought that I should have my source of low-grade heat from this river. I was then faced with the necessity either of pumping water some 90 ft vertically or of conveying heat a similar distance, and this seemed an uneconomic arrangement. At about this time, however, alterations consisting of digging out a certain amount of space under the floor of half of my house were in progress. During this excavation it was discovered that the temperature of the water which percolated under the house foundations and into a temporary sump did not seem to vary very much from 48° F, irrespective of the outside weather conditions. As this water temperature was presumably also the soil temperature, a solution to the problem of the source of low-grade heat was at hand. As the basement area was in a state of excavation there was little further difficulty in digging a few shallow trenches and putting in some 400 ft of copper piping.

When all this work was completed, an experimental air-cooled heat exchanger and a 3 h.p. 3-cylinder compressor were acquired. An induction motor was used to drive the compressor through V-belts, and an axial fan to circulate air over the heat exchanger. The whole arrangement was piped up and filled with Freon, and after the usual initial difficulties the unit actually produced hot air at the back of the radiator. A sheet-metal duct was then made to carry hot air to the dining-room, and provision was made to complete the air return circuit to the basement. This arrangement was also successful.

Unfortunately, accurate records were not kept of this early work, but with an outside temperature in March, 1949, of around 30° F, the temperature in the dining-room could be maintained at about 75° F. As this indicated that there was more heat available than was required, it was decided to heat the hall and passage-way. Another duct was run and shutters were placed in each duct so that some control of the amount of air entering the dining-room and the hall could be obtained. Adjustment of these finally gave average temperatures in the dining-room of about 63° F and in the hall of about 58° F, with the outside temperature at about freezing-point, and for two years this method worked splendidly.

During the 1951–52 heating season, further excavations became necessary and so the opportunity was taken to lay more piping. The unit was recoupled with all these pipes in series, making a total pipe length of some 1 000 ft. Once again more heat with a little to spare was obtained, and so a further room was ducted and heated. The total heat available, however, was not quite adequate to maintain the average desired temperature of about 62° F throughout the entire house, and it had been decided to carry out a further experiment in a small room which suffered from dry rot.

Soil under this room was excavated to a depth of 4 ft and some concrete was placed there to prevent further troubles from rising damp and dry rot. The room was repanelled with hardboard about 4 in clear of the stone wall, and a duct was laid into the room below the floor. A small controllable vent was provided on the roof so that a leakage path could be arranged, and ducts were also made through the skirting so that the heated air could come directly into the room from the space under the floor.

In order to obtain the additional heat required to deal with the whole house, and since the pressure drop through roughly 1 000 ft of pipe in series was something like 15 lb/in^2, the two halves of the coils were paralleled, each having a separate expansion valve, and the size of the compressor was increased to 5 h.p. So far, no details have been taken of the latest unit, but there is now sufficient heat to maintain the entire house at an uncomfortable 72° F with an outside temperature of 38° F. Experience has shown that, to heat the 26 000 ft^3 content of the entire house, the unit running for an average of 5½ hours a day with an input of 5 kW will maintain the temperature at approximately 62° F, even if the outside temperature falls 20° F below freezing point.

While all this was going on, it was decided to try the effect of a domestic hot-water heat pump, using atmospheric air as the low-grade heat source. This unit, with an input of 600 watts, maintains a 68 gal tank of water at 120° F with an ambient temperature of 55° F. The unit was run on a thermostat for 12 months exactly, with a recording hour-meter in circuit, and the average daily running was found to be only 5·5 hours.

Dr. Macfarlane is with the Macfarlane Engineering Co., Ltd.

A 2 kW immersion heater was substituted for the heat-pump coil in the same tank and allowed to run under exactly the same conditions. It was found that this ran for an average of 4·875 hours per day. These figures show nearly a 3 : 1 running cost in favour of the heat pump.

My personal experiences, although they are not very broad, confirm me in my impression that the heat pump cannot be neglected much longer, and that as a source of space or water heating there is at the moment no more efficient method and in the long run no cheaper method.

Abstract No. 2285
Feb. 1957

SOUTH-WESTERN SUB-CENTRE: CHAIRMAN'S ADDRESS

By W. ROY ROWE, Member.

'AUTOMATION IN THE HOME—ITS ORIGIN AND DEVELOPMENT'

(ABSTRACT *of Address delivered at* EXETER, 18*th October*, 1956.)

Although this is the age of electricity, in which at the mere flick of a switch we can automatically command the service of so many labour-saving devices, it is interesting to reflect on the electrical development which has taken place to enable such a large percentage of the population to enjoy a higher standard of living, and the Address gives a brief review of the origin and development of some of the appliances used in the preparation, cooking and storing of food, together with washing and cleaning aids for the household. Methods of obtaining heat are traced from the Old Stone Age to the present time, clearly indicating the similarity of the principles employed in the electrical equipment now used in the home.

In considering in more detail the specific development which took place in electric cooking from the commencement of the 20th century, it is interesting to note that the early models were of a battleship construction and were more than likely to have been an electrically operated conversion from gas, but as the charge for electricity was at the flat rate of 6d./kWh and upwards, the cost of electric cooking was unattractive. Between the two wars there was a breakaway from the gas tradition and cookers were designed for the express purpose of electric cooking, the models being constructed in many ways similar to those of to-day.

Reference is made to the super-speed boiling-plate of the early 'thirties using a low-voltage double-wound transformer. Details of a further development for rapid boiling are mentioned, whereby the inner ring of a double-circuit plate is connected to the mains for about half a minute; hence, with a 1 800-watt plate, during the heating period a half-section designed to take 900 watts at 120 volts is made to operate at 240 volts, thus presenting a load of about 3·6 kW. By this means it is possible to boil a pint of water in about 4 min, which is comparable with gas.

The developments which took place prior to 1939 were many, including the introduction of the first oven thermostat, the appearance of plug-in hotplates and solid-type grill-boilers, together with vitreous enamelling on all the sheet-metal components, including the hob. In the early post-war years the E.D.A. specification for interchangeable replacement parts was introduced, relating to boiling-plates and grill-boilers. The establishment of more and more simmering controls and radiant plates gave greater flexibility to control, and recently, with the advent of the timer control, the electric cooker has taken the lead over other forms of cooking equipment.

The closest connection to cooking is the provision of hot water, which is a necessity for culinary purposes but was not looked upon as essential for personal cleanliness until a somewhat late period in history.

[Lantern slides were shown of interesting examples of old-type heaters, one in particular with the electrical switch control interlocked with the cold water valve.]

Mr. Rowe is with the South Western Electricity Board (Cornwall Sub-Area).

Although maximum efficiency of the heating element appears to have been achieved, water heating design in many other directions will have much to interest us in the coming years, for at the present time 50% of our homes rely on solid fuel for hot water, and 30% of these installations are over 50 years old. Furthermore, 15% of our homes heat water in a pan or kettle only.

A family of four has an average need of 250 gal of hot water at 140° F a week for baths, laundry, personal washing, etc., and this gives some indication of the enormous electrical load which can be anticipated from this source, particularly as when properly applied the apparatus is the best of all current-using devices in terms of units consumed in relation to incidence of peak load.

Early history tells us that snow, ice and water have been aids to mankind for the purpose of preserving foods. Refrigeration is as old as civilization itself, earthenware dishes and cold water having been used by the Ancient Greeks and Egyptians. Snow from the mountains was used after the Roman conquest of Britain, and oysters from the Thames Estuary were exported to Rome packed with snow. At a later period the tea clippers returned loaded with ice to tropical lands.

The progress of refrigeration continued slowly for many years for industrial and commercial purposes, but it was not until the First World War that the first domestic refrigerator appeared in the United States, and it was 1925 before any kind of marketing took place. In the last 13 years the main advances in refrigeration have taken place in America, where, owing to climatic conditions, the sales have been phenomenal. Almost 9 out of 10 households have a refrigerator in America; in this country almost the same number are without one.

The Address goes on to describe the development of the compressor and absorption type of refrigerator unit.

Paradoxically enough, a refrigerator can be used for space heating—the heat pump takes in heat at a reasonably high level, as, for instance, by slightly cooling the water in a river or even by cooling the ground and rejecting this heat at a fairly low level to a refrigerating system.

Turning now to the household chore of washing and cleaning, this if anything, requires automation.

In mediaeval times there was little washing done at all; the nobility wore taffeta and silks without any underclothing. The poorer classes wore coarse woollens. No washing could cleanse the clothes without spoiling them; dyers were employed, but all they managed to do was to conceal the dirt.

Other aids for the more fortunate were hand-operated dollies and rocking machines to turn the water round the clothes. As the 20th century wore on boiling coppers, drying racks and irons were aids that came into use.

Reference is then made in the Address to the various oscillating gyrator principles which were employed and developed for the electric washing machine. Electrical engineers can take credit

for the fact that the installation of an electric washing machine with power-driven wringer, and an electrically operated ironer, automatically raises a home to the standard where economy in cleanliness is not considered.

If we could look back along the corridors of time we should see at every twist and turn of the way the symbolical figure of a woman—with a broom in her hand. Their present-day passion for cleanliness is new only in degree—it has always been a dirty, dusty old world, and it has always been a woman's job to sweep it up!

Just at the turn of the century the first vacuum cleaner was invented. Vacuum cleaners were originally operated manually with the aid of bellows, as very few private houses had electricity. To-day, three out of every four middle-class homes use an electric vacuum cleaner, but only one in three working-class households have been persuaded to use this appliance. Examples of cleaners manufactured in the 'thirties indicate the very limited advance which has taken place since then.

Turning to trends and future developments, reference is next made to the dielectric-heating cooker now being manufactured in the United States. This will fry an egg in 20 sec and bacon in 75 sec, but takes 90 min to cook a whole turkey. Metal cooking vessels would have a shielding effect, so that plastic or Pyrex type dishes must be used. As a concession to popular taste, a grill is added to give a surface browning to the meat after cooking.

Signs and portents there now are that, before many years have passed, we shall have left the electrical age for the electronic age, in which all sorts of tasks now performed laboriously by complex machinery will be done with a simplicity and ease so far undreamed of, except perhaps by science fiction writers.

It has been found that semi-conductors give heat when current is passed one way and extract heat when current is passed the other way; conversely, heat can cause current to flow in the material. Ice cubes have been produced by means of this principle, although the efficiency is at present less than that of an ordinary refrigerator. It is possible to visualize a domestic combined heating and refrigerating installation where heat is abstracted from the larder and put into the water tank, all without any of the mechanical complexities entailed in the present-day heat pump. A semi-conductor unit exposed to the sunlight might generate all the electric power needed for many of the other domestic purposes. Indeed this makes one think that the electrical industry has mothered a queen cuckoo in electronics.

In conclusion, reference is made to the scope and magnitude of the work that lies ahead; for at present only one in four consumers has an electric cooker and a vacuum cleaner; one in five, an electric water heater; one in seven, a washing machine; and, as already mentioned, one in ten, a refrigerator.

Yesterday marked the official beginning of large-scale nuclear generation of electricity* with all its limitless possibilities, but it seems fitting that we should have cognizance of the development which has taken place throughout the ages, to the present achievement, with its promise of revolution in the production and utilization of electrical energy.

* Calder Hall, 17th October, 1956.

Abstract No. 2314
Feb. 1957

WEST WALES SUB-CENTRE: CHAIRMAN'S ADDRESS

By J. L. GRIFFITHS, Associate Member.

'REVIEW OF ELECTRICAL DEVELOPMENTS IN THE STEEL AND COAL INDUSTRIES OF SOUTH WALES OVER THE LAST 25 YEARS'

(ADDRESS *delivered at* SWANSEA, 11*th October*, 1956.)

Economic Situation in the Early 1930's

The situation 25 years ago in South Wales was vastly different from the prosperity which is evident on every hand to-day. The demand for British coal in 1933 was only 54% of that in 1923, and the average number of British mineworkers employed had dropped from 1 100 000 in 1913 to 803 000 by 1932, so that unemployment was very serious generally and particularly in South Wales. In the ferrous metal industries a similar situation prevailed. Production of iron and steel in the area had fallen by 1931 to between 30% and 50% of the 1929 values, and at the peak of unemployment in December, 1930, nearly two-thirds of all South Wales steelworkers were out of work.

Technical Situation in the Early 1930's

Coal Mining.—There are records of small electric drives, mainly for pumping purposes, in some British coal mines extending back to before the turn of the century, and development and extension of these initial experiments had proceeded until, by 1930, many of the mineowners were favourably disposed towards electric drives in general. However, some mining engineers still raised technical objections to electric winders, haulages and coal cutters, and preferred steam drive for these machines. There was a considerable weight of experience behind them, too, as at that time steam provided the great majority of the power used in all British mines, much of the haulage work underground being done by horses and ponies.

Iron and Steel.—In the metal industries, in 1930, the whole position of South Wales was very weak. Much of its steel-making plant was old, and the depressed state of trade made it difficult to obtain new capital to build modern integrated iron and steelworks. At the finishing end the weaknesses were even more apparent. Continuous wide-strip production and cold reduction had begun to revolutionize the finishing industry, but many of the South Wales plants had been installed around the turn of the century, and some were not well sited in relation to their supplying steelworks. Steam drives had been dominant for many years, although Diesel engines were offering strong competition, and electric motors were a relative newcomer to the field.

Developments Since 1930

Coal Mining.—The history of developments in coal mining since 1930 has not generally been characterized by a series of startlingly new innovations, but rather by the gradual application, extension and improvement of equipment whose principles were well known in 1930.

In general, the reasons for this rather slow and steady pace were economic rather than technical. Many mines that could probably have been re-equipped to work more efficiently in the early 'thirties were prevented from doing so by lack of capital

Mr. Griffiths is with the English Electric Co., Ltd.

and of demand for the coal. Equally, the increasingly rapid pace at which the mechanization of colliery activity has been carried out in recent years is due, not so much to sudden improvement in the machines available, as to the larger capital available after nationalization in 1947, and to the urgent need to extend the production of the already undermanned teams of underground workers. In the more usual fields for power application in the collieries, i.e. haulage, pumping, winding and ventilation, the power increases in installed capacity since 1938 vary from 50% to 80% approximately, and are indicative of the general movement towards increased electrification. The most interesting comparisons, however, are the increase in coal-cutting machinery from 170000 to 372000h.p., and the increase in conveyors and loaders from 71000 to 517000h.p. The first may well be considered to be an indication of the increasing confidence of the colliery officials and workers in electrical flameproof equipment at the coal face; the second is a graphic indication of the extent to which manpower shortage has made mechanical handling in the mines of vital importance.

Probably the most significant feature in the development of mining equipment over the past 25 years has been the ever-increasing robustness and reliability which has had to be built into it to make it suitable for the arduous conditions of work in a colliery. A most notable part of this special development is, of course, the development and perfection of the system of testing and certification of flameproof equipment by the Mines Department Testing Station at Buxton, and the development by the manufacturers of equipment which can meet these tests.

Apart from flameproof gear, the greatest amount of special development of electrical equipment for mining purposes has probably been done on the winders and associated control equipment. Two systems are in fairly general use here, the d.c. winding motor driven by a Ward Leonard or Ward Leonard Ilgner set, and the a.c. slip-ring induction motor with external rotor-resistance speed-control equipment.

The Ward Leonard system has many advantages of accurate speed control, and the simple application of regenerative braking means that the operation is precise and economical, and the life of the mechanical brakes is relatively long.

The a.c. winder is cheaper in first cost than the Ward Leonard system. The equipment occupies less space and is more economical if the frequency of winding is low. There is a higher peak demand at starting and during acceleration period than with a d.c. hoist. In general the a.c. type of winder is more common for the newer British colliery installations. It has, however, a disadvantage in that it is less economical than the d.c. type when the frequency of winding is high, or when much lowering of loads is done by counter-current braking. But by the installation of d.c. dynamic-braking equipment, the lowering of loads may be carried out with economy comparable with that of the Ward Leonard hoist.

This section may well conclude with a quotation of two recommendations made by the Reid Committee set up in 1944 by the Minister of Fuel and Power to investigate the position in the coal industry:

> New mines shall be laid out on an all-electric basis, and wherever practicable the complete electrification of existing mines should be seriously considered.
>
> A careful examination should be made of generating stations serving individual mines to determine whether their continued operation is warranted, or whether they should be replaced by a central generating station or by public supply.

The importance of electrification in all mines could not be indicated much more clearly.

Iron and Steel.—Unlike the gradual progress described in the coal mining industry, the advances made in the last 25 years in the South Wales iron and steel industry were effected in a few large jumps, mainly by the construction or reconstruction of several large plants.

The first of these developments came in the mid-'thirties with the commissioning of a major electrified steel plant. Following this, in the late 'thirties came the first major modernization of the finishing trade. Just before the Second World War, plans were being considered for another integrated plant, but the war stopped these developments. However, the idea was revived again in 1945 after the cessation of hostilities, and since then the plan which envisaged the modernization of both the steel making and the finishing sections of the industry in three major plants has been completed. This included a new iron and steel plant and wide strip mills with a slabbing mill which is amongst the largest in the world.

The second modernization of the finishing trade included cold reduction mills and three tinplate mills capable of speeds up to three times greater than that installed in the first modernization scheme.

By these major projects, the South Wales steel and tinplate industries have been revolutionized and established once more in their fully competitive position in the world markets.

The primary feature which has made these projects so efficient is largely their extensive adoption of electrical drives and the controls which are possible as a result.

The developments described are all examples of the manner in which the increasing application of electricity to the metal and coal mining industries of South Wales has constantly improved the efficiency of the industries and resulted in increased prosperity for the area as a whole.

[Figures are quoted from the 'Ministry of Fuel and Power Digest, 1955', with the permission of the Controller of H.M. Stationery Office.]

621.311.21(71)

Paper No. 2204 S
Feb. 1957

THE NEW SIR ADAM BECK GENERATING STATION AT NIAGARA

A Major Canadian Hydro-Electric Development

By R. L. HEARN, B.A.Sc., D.Eng., M.E.I.C.

(Lecture delivered before the Supply Section, *16th May,* 1956.)

(1) INTRODUCTION

With the ratification of the Niagara Diversion Treaty between Canada and the United States in October, 1950, the construction forces of the Hydro-Electric Power Commission of Ontario were clear to begin the actual work, and ground was first broken in January, 1951, less than three months later.

The new Sir Adam Beck–Niagara Generating Station No. 2 involves eight principal sections, some of which proved to be rather unique problems in design and construction. These sections included: (*a*) a control dam on the Niagara River; (*b*) two separate intakes of the Johnson–Wahlman type on the shore of the Niagara River, some two miles above the Falls; (*c*) two parallel concrete-lined tunnels about 5½ miles long and 45 ft in finished diameter; (*d*) an open canal 200 ft wide and 2¼ miles long; (*e*) a forebay with headworks at the top of the gorge above the powerhouse; (*f*) 16 concrete-encased steel penstocks 19 ft in diameter; (*g*) a powerhouse located 6 miles downstream from the Falls and containing the generating units, each consisting of a turbine with a rated capacity of 105 000 h.p., directly connected to an 80·5 MVA generator; (*h*) a pumped-storage development. The general layout of the works, for both the new station and the old, is shown in Fig. 1.

The reason for taking the water from a point some 2 miles above the Falls and using it at a location 6 miles below the famous Cataracts was to make the best possible use of the head resulting from the natural fall of the river. At mean levels there is a total fall of 326 ft in the Niagara River from Lake Erie to Lake Ontario; of this, 225 ft occurs at the Falls and in the rapids extending for about a mile above them, and a further 90 ft occurs in that part of the river from the base of the Falls to Queenston, where the powerhouse is situated. Early developments made use only of the drop close to the Falls and neglected entirely the potential in the lower river.

The new development adheres to the principle of utilizing as much of the available head as is economic, but takes cognizance of the immense development of the area in more than 30 years since the No. 1 station was built. It was considered inadvisable to impose the additional interference on the movement of surface traffic that would result from the construction of one or more open canals in the area, and so tunnels were chosen as more suitable.

(2) THE REMEDIAL WORKS

It will be appreciated that the diversion of such large amounts of water from the river for the purpose of power development, thereby reducing the flow over the Falls to the permissible minima named in the Treaty of 1950, cannot fail to have a considerable effect on water levels in the river itself and, to a lesser degree, on Lake Erie. The distribution of flow would also be altered and the scenic spectacle adversely affected: this was visualized in drafting the Treaty, and Article II provides for the construction of suitable remedial works.

The works recommended and now nearing completion consist in excavation and fills near the flanks of the Horseshoe Falls, to maintain an unbroken curtain of water over the crest at all times, and a control dam at the outlet of the Chippawa–Grass Island Pool about a mile above the Cataract, and therefore above the cascades which extend for rather more than half a mile above the Falls.

The control structure (shown in Fig. 1) will extend 1 482 ft into the river from the face of the abutment on the Canadian shore and will have 13 sluices, each with a clear span of 100 ft, separated by piers 14 ft wide and 91 ft long. The control dam is being built in sections of two or three gates at a time. Thus, only a small part of the river channel will be obstructed at any time by the cofferdam enclosing the section under construction. Four sluices are now completed and operating.

Velocities in the section of the river where the control structure is being built are high, and the flow is very turbulent. Construction of the cofferdam in the area, therefore, was a problem to which much thought was given in the planning. The method developed has proved to be eminently satisfactory and warrants a description in some detail.

Immediately adjacent to the shore, extending out into shallow water, a section of the cofferdam was built using rock-filled timber cribs of conventional design; beyond this, structural-steel cribs top-loaded with concrete blocks were used. Each crib is 10 ft by 30 ft, and was lowered into place adjacent to the one previously placed by means of a crawler crane. A series of interlocking rollers keep the crib in alignment with the previous one, as it is lowered close to the bed of the river, its 30 ft dimension being upstream and downstream.

After it is placed, heavy H-sections are inserted in guides and lowered until they are in contact with the river bed; they are then driven to secure good bottom bearing. The portion of the H-section projecting above the top of the crib is cut off at the deck level and the crib is top loaded with 36 precast concrete blocks, each 10 ft by 2½ ft by 3 ft and weighing 6 tons. Crib placing continued in this manner until both the upstream and downstream sections of the cofferdam were completed, and the section joining their extreme ends was built in a similar manner. Steel-sheet piling was then driven on the river faces of all sections of the cofferdam, penetrating into the rock to provide a seal. Earth toe-fill along the base of the cofferdam then rendered the structure watertight.

The loading of the crib is carried by the H-columns, and the cofferdam is designed to be stable against the maximum water pressure. To make it secure against the excess pressure that might result from ice accumulation upstream, heavy struts were installed after the area was dewatered. The cofferdam has proved exceptionally tight, and the whole enclosed area for one section was pumped dry in the course of one day.

The actual control structure is so designed that additional sluices may be added, if necessary, at the outer end. It is surmounted by a service deck 25 ft in width, carried on prestressed flat-arch beams of pleasing proportions, spanning from pier to pier.

The operating machinery for the gates is entirely below the level of the service deck and is located in the piers. Various types

Dr. Hearn is Chairman of the Hydro-Electric Power Commission of Ontario.

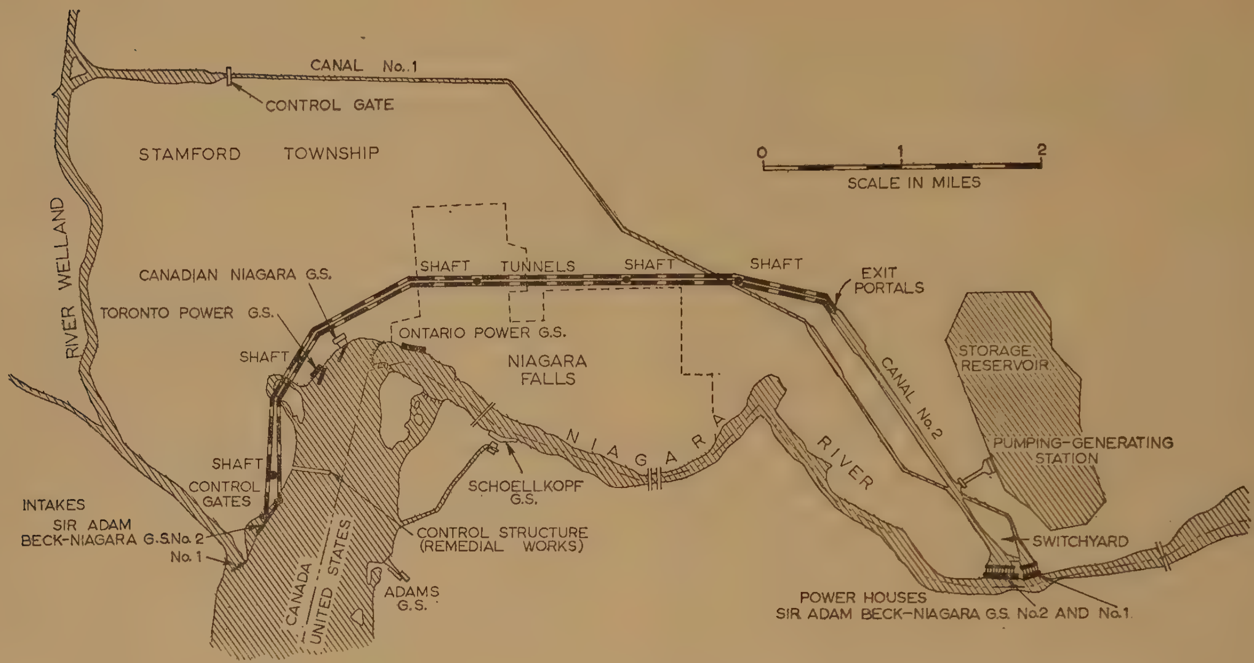


Fig. 1.—Map of the Niagara Falls area, showing the existing stations and works and the new civil-engineering projects associated with the No. 2 generating station.

of gate were considered and carefully studied. The choice finally rested on a submersible gate of the 'fish belly type' secured to the sill by 18 hinges, which take the thrust, and having trunnions at the ends with centres at elevation 552·5, or 1 ft below the sill level. To open the sluice the gate is lowered into a depression downstream from the sill, and when fully open its surface is at approximately the same level as the sill. Thus, in the fully open position there is nothing to retard the flow of water or ice through the sluice.

The trunnions fixed to the ends of the gate are also the driving discs, and are provided with seals where they pass through the walls of the piers. Within the piers they are equipped with a heavy lever connected to the operating mechanism. Hydraulic operating cylinders are mounted above maximum water level, and the piston rods from these engage the end of the lever.

Normally, the two hydraulic cylinders, one at each end of the gate, will be used to raise or lower the gate, but the design is such that a single cylinder can exert sufficient operating force to open or close the gate should the other become inoperative. The gates will be controlled from a single control room located on shore, or can be operated individually from the piers.

The purpose of the work at the flanks of the Horseshoe Falls is to assure such a scenic spectacle as will result from a flow per foot in the tourist season approximately equal to that of the American Falls, and will provide an adequate coverage of the crest at other times.

(3) THE INTAKES

The Niagara River is well known, not only for the scenic beauty and attraction of the Falls, but also for the destruction caused by ice jams. Under certain conditions of temperature and wind, flowing ice on the river has been known to reduce materially the output of the present plants and to cause complete shutdown of some of the older ones. The problem in the selection and design of the intake works therefore resolved itself into two elements: (*a*) to extract some 40 000 ft^3 of water per second from the river with a minimum of head loss without too much interference with natural flow conditions, and (*b*) to prevent the intrusion of flowing ice into the water-conveying system.

Various studies were made of the types of intake and their location on the river in relation to the overall plan of development. Following the decision to use tunnels, the choice of the intake site was almost automatic. The chosen location provided the take-off point for the shortest tunnel route to Queenston, keeping it on the Canadian side of the International Boundary, and the maximum obtainable head concentration of the river.

In considering the intake design for the No. 2 plant, it was logical that serious consideration should be given to the adoption of a gathering-tube type of intake, since it was developed initially to meet the local conditions on the Niagara River. From a review of existing installations and studies carried out by the staff, it was evident that such a structure, located along the shore parallel to the flow lines of the river and with the entry slots located in the vertical outer face, would be desirable hydraulically and would not detract from the natural beauty of the Niagara Park lands along the river. Located in this manner, it permitted unimpeded progress of flowing ice past the structure.

Investigations were carried out in the Niagara model of the structures and adjacent river conditions (built to an undistorted scale of 1 : 36) to obtain the best location, the length of the structures, and the necessary riverbed excavation.

The preliminary design for the structure was made, based on the Johnson–Wahlman theory.* The theoretical approach proved unsatisfactory for this application, doubtless owing to the high velocities and currents in this region of the river. The original theory was actually based on taking water from a still pool.

The first intakes tested in the Niagara model represented structures each 1 000 ft long; however, progressive tests indicated that equally good performance could be obtained from gathering tubes only 500 ft long, at a considerable saving in cost in both the structures and the dredging required outstream in the river

* See the report by R. D. JOHNSON and P. WAHLMAN: 'Design of Intake for 15 000 ft^3/sec' (New York, 1920).

to improve entry conditions. Having established the basic dimensions of the tubes, more detailed hydraulic investigations were then undertaken.

Two theoretical designs were developed and models were constructed. One was designed to have constant acceleration of the water inside the tube and the other was a compound tube having constant velocity for the upstream half of the length and a constant acceleration for the remainder. The interior dimensions of each of these designs were reduced progressively by moving the back wall closer to the front wall and raising the bottom at the upstream end to form a tapering tube. This procedure was continued through a series of tests until the overall energy loss began to rise. It must be realized that, at that time, no structural design work had been started, so that the quantity of excavation was an index of overall cost. Studies indicated that the head loss was practically constant over a range of internal dimensions from a 20 ft tapered tube to a 45 ft square uniform tube. However, any reduction below the 20 ft tapered section resulted in increased losses. Therefore, a basic design for the tube was adopted in which the length was 500 ft and the cross-section varied from essentially a 20 ft square at the upstream end to a 45 ft square at the downstream end.

Following the determination of the optimum interior dimensions, attention was directed to the area of the slot opening. The model was constructed having fixed piers set at 45° to the longitudinal axes of the structure, and the remaining components were so constructed that the sill elevation, the sill and lintel radii, and the slot height might all be varied. Previous tests had indicated that, for this application, variable vane angles had only a minor effect on the overall performance of the model. Studies indicated that there is no appreciable decrease in energy loss for slot areas in excess of 2 900 ft^2 based on either variable river or sill elevation: in general, it was found that the smaller the slot the larger the loss. However, increasing the slot area beyond that selected resulted in very unstable operating performance under varying river flow conditions. A sill elevation above 537·6 ft tends to increase overall energy loss slightly, and for other considerations this elevation was adopted as the maximum allowable to permit adequate submergence of the top of the slot.

From the results of the tests it was possible to fix the sill elevation at 535·75 ft, in order to keep the lintels well below water surface, the sill and lintel radii at 4 ft and the slot area at 2 900 ft^2. In the meantime, structural analysis indicated that the piers in the slot should be about $2\frac{1}{2}$ ft thick and spaced at 16 ft 8 in centres. Tests had indicated that, within limits, pier thickness and spacing had very little effect on performance. The model was then reconstructed incorporating these features but with an adjustable slot height.

The remaining feature to be determined was the height of the slot to produce uniform draught distribution throughout its length. Tests were continued and a slot height was found which produced, for natural river conditions, approximately equal draught in each 100 ft section (within 1%).

At this time, however, a new variable was introduced into the overall scheme. It was found that, in order to utilize the full diversion for power purposes in accordance with the terms of the Treaty, a control dam would be required to regulate the levels of the Chippawa–Grass Island Pool. With the gates closed in this dam the natural flow pattern in the river adjacent to the intakes was altered, and it was found that equal draught distribution for this condition could be obtained only by a slot of different dimensions. A compromise slot shape was therefore adopted, since the intake would have to operate under both conditions. The slot height adopted varied from 13·3 ft at the upstream end to 7·5 ft at the downstream end, and the taper was uniform. The maximum variation from uniform draught in any 100 ft section for either condition is 4%.

The general dimensions of intake No. 2 are the same as for intake No. 1. However, it was found necessary to vary the vane or pier angle and to introduce a non-uniform tapering slot to achieve comparable performance.

A funnel-shaped excavation in the river bed extending upstream from the structure about 1 000 ft and outstream 750 ft was made to intersect a large cross-section of the flow and attract a flow past the structure about 50% in excess of that to be diverted.

The general layout of the No. 1 intake structure consists of a tapering box section 500 ft long with the width and height varying from 20 ft to 45 ft from the upstream to the downstream end. A uniformly tapering slot was formed in the vertical face on the river side which varies in height from 13 ft 4 in to 7 ft 6 in in the upstream-downstream direction. Concrete piers or guide vanes were set into this slot at an angle of 45° to its longitudinal axis at 16 ft 8 in centres.

The overall dimensions of the second tube are essentially the same, except that the slot is larger at the upstream end (17 ft) and smaller at the downstream end (6 ft 1 in), has a non-uniform taper and the vane angles vary: five upstream vanes are at 55°, the next seven are at 45° and the remainder are at 40°. The selection of these three angles rather than a constantly changing vane angle resulted in considerable economy in form costs, since prefabricated steel forms were used for this detail. Three such forms were sufficient for the construction of both intakes.

The sills of the slots are approximately 25 ft below the normal river level, the lintels being a minimum of 8 ft and a maximum of 19 ft below the normal water level.

The engineering design of this box-like structure presented many problems. Preliminary stress analysis indicated that it would not be possible to design it as a continuous frame, owing to the inability of the small cross-sectional area of the vanes to resist the major bending stresses. The vanes are approximately 11 ft long, 2 ft 6 in wide, semi-circular shaped at the ends and are set at an angle to the induced stresses. Therefore continuous horizontal hinges were introduced in the structure above and below the vanes. The structure then resolved itself into a rigid frame with two hinges at the vanes. The vanes act structurally as columns supporting the roof, but are not subjected to bending stresses.

Downstream from the gathering-tube slot a 45 ft square conduit continues for a distance of about 120 ft to a control structure. This contains a control gate having a clear span of 45 ft, a height of 58 ft and a weight of 200 tons, which may be raised or lowered by an electrically-operated screw-and-nut arrangement. The gate functions only when it is necessary to isolate a tunnel for inspection or other purposes.

The conduit continues downstream from the gate structure for about 500 ft, changing from the square to a circular shape, 45 ft in diameter, to join with the tunnel proper.

(4) THE PARALLEL TUNNELS

The design and construction of the twin tunnels posed some interesting problems, all of which were again overcome as the result of tests made on models. The tunnel work consisted of twin bores on 250 ft centres, each with an excavated diameter of 51 ft and a finished diameter of 45 ft when lined with concrete. Tunnel No. 1, which follows the outer course around the Niagara River, is 28 560 ft long, and No. 2, which follows the inner course, is 27 300 ft long, making a total tunnel length of 10·6 miles. Each tunnel is designed to carry 20 000 ft^3/sec, although tests showed a possible capacity of 23 000 ft^3/sec.

The first decision was in connection with the 48 ft-wide and

58 ft-high tunnel control gates, which are installed immediately downstream from each intake in the 45 ft-square covered conduits connecting the intakes with the tunnels proper. A transition from the 45 ft-square conduit to the 45 ft diameter tunnels takes place immediately below the gates. Each gate is designed to close under full-load tunnel flow, to open under full upstream head and forebay level downstream, and to open under full upstream head and no tailwater level, or, in other words, an empty tunnel. The speed of travel of the gate is set at 4·5 in/min as the result of other studies where surge and water-hammer effects in the tunnel were investigated.

In view of the size of gates and the magnitude of the tunnel velocities—about 10 ft/sec at the gate under design flow—it was decided that a model would be constructed by the Ontario Hydro-Electric Commission to determine the actual hydraulic forces that would exist under design conditions. The hydraulic load measurements were made by electrically indicating strain gauges mounted in the wheel supports and the hoisting apparatus. These gauges indicated loading by the amount of change in surface strain which took place in their mountings and were connected by wires to an electrical bridge circuit which indicated the movement in microinches.

With regard to the horizontal thrust under lowering conditions, it was found that at all times it was less than the static thrust with the gate closed with no tailwater, which was a further design condition. Since the downpull forces were large, a number of modifications were made to the gate bottom to determine how the shape affected the downpull. As a result of these tests, a satisfactory gate-bottom design was chosen and the hoisting apparatus was designed for the loads to be encountered.

The alignment of the 45 ft-diameter tunnels required 11 bends in tunnel No. 1 and 10 bends in tunnel No. 2, the majority having a deflection angle of about 30°. In view of the size of the tunnels, the number of bends, the scarcity of information on bend losses (other than 90° bends) and the great value of minimum head loss, it was decided to make laboratory tests of bend loss to determine the optimum R/D ratio (bend-radius/pipe-diameter) for a bend and the actual bend-loss coefficient.

A very intensive series of tests were made using 6 in pipe and bends of 30°, 60° and 90° deflection angles. Bends of five different radii were used, producing R/D ratios from 1·42 to 41·37.

From these tests, R/D ratios were chosen for the tunnel bends which would give minimum bend losses, and the bend-loss coefficients were used in estimating the total losses from the bends. While it is fully recognized that the 6 in pipe produced Reynolds numbers much below those for the 45 ft tunnel, it was felt that the R/D ratio giving the minimum bend loss would remain virtually unchanged and the bend-loss coefficient would be conservative, since the larger tunnel would probably produce lower bend losses. These results are a valuable addition to bend-loss literature, for they indicate the relative effect on bend loss of a good range in R/D ratio and a deflection angle range of from 30° to 90°, using precisely the same pipe in each case.

Actual construction was carried out through five vertical shafts common to both tunnels. Shaft depths were determined by the elevation of the 10 ft-thick stratum of Irondequoit limestone, selected as the most satisfactory rock layer to use for the tunnel roof. It is interesting to note at this point the geological formation common to that area (see Fig. 2). In sinking the shafts, the following layers were encountered: silt; clay, with some gravel; hard red silty sand; fine red sand with a few boulders; silty clay, gravel and boulders; Guelph–Lockport dolomite; Gasport limestone; Decew dolomite; Rochester shale; Irondequoit limestone; Reynales dolomite; Neagha shale; Thorold sandstone; Grimsby sandstone; Power Glen shale; and Whirlpool sandstone. All shafts were excavated to a depth below the tunnel invert grade to provide a pocket for the muck storage bin and the skip-loading mechanism.

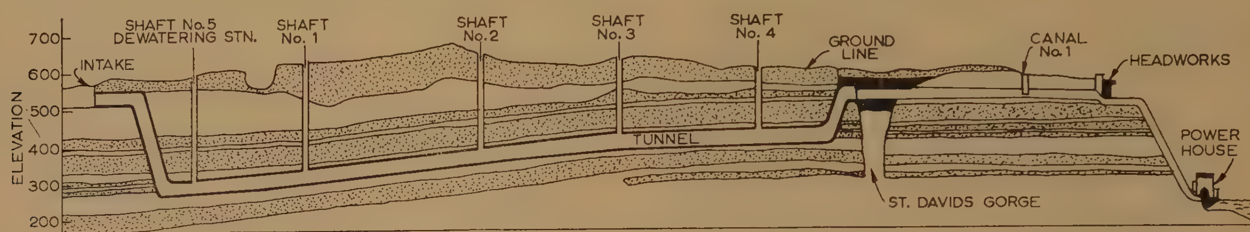


Fig. 2.—Geological profile of the Niagara Falls area showing how the fullest use has been made of the head between the upper and lower sections of the Niagara River.

With the shaft completed, tunnel construction was immediately started, applying the method that had been decided upon, i.e. completing the upper or heading section before starting the bench section. In spite of the generally excellent roof formed by the Irondequoit limestone, the weak Reynales dolomite and Neagha shale beds underneath it made continuous roof support necessary. Bench excavation was started only after the upper or heading section had been completely holed through and the bottom thoroughly cleaned.

Concrete lining for the tunnels was poured in three stages, namely the curb, the invert and the arch. The curb was poured directly following the bench rock excavation and served as a roadbed for the movable-form travellers and equipment used for the invert and arch concrete pours that followed. Grouting operations began 90 days after the arch concrete had been poured, and this work was the final step in completing the tunnel.

From intake to outlet portal the tunnels are inverted siphons with the lowest point at shaft No. 5—that nearest the intake. At this shaft a dewatering station has been built in the crosscut between the tunnels so that they can be drained for inspection or repairs. The pumping station contains eight submersible-type 4-stage pumps each directly connected to a totally-enclosed oil-filled submersible 450 h.p. motor supplied with power by marine-type cables from controls at ground level. The station is so designed that even if it is entirely flooded the pumps can be operated. Each pump has a rated capacity of 4 000 gal/min against a head of 340 ft. The pumps draw water from a header connected to both tunnels and will be capable of draining either tunnel in less than seven days.

(5) THE OPEN-CUT CANAL

As the tunnels approach the outlet portal they rise at an angle of 30° and converge to discharge their flow into the open canal leading to the forebay. The portals are at the southerly side of St. David's Gorge, a prehistoric river channel filled with drift

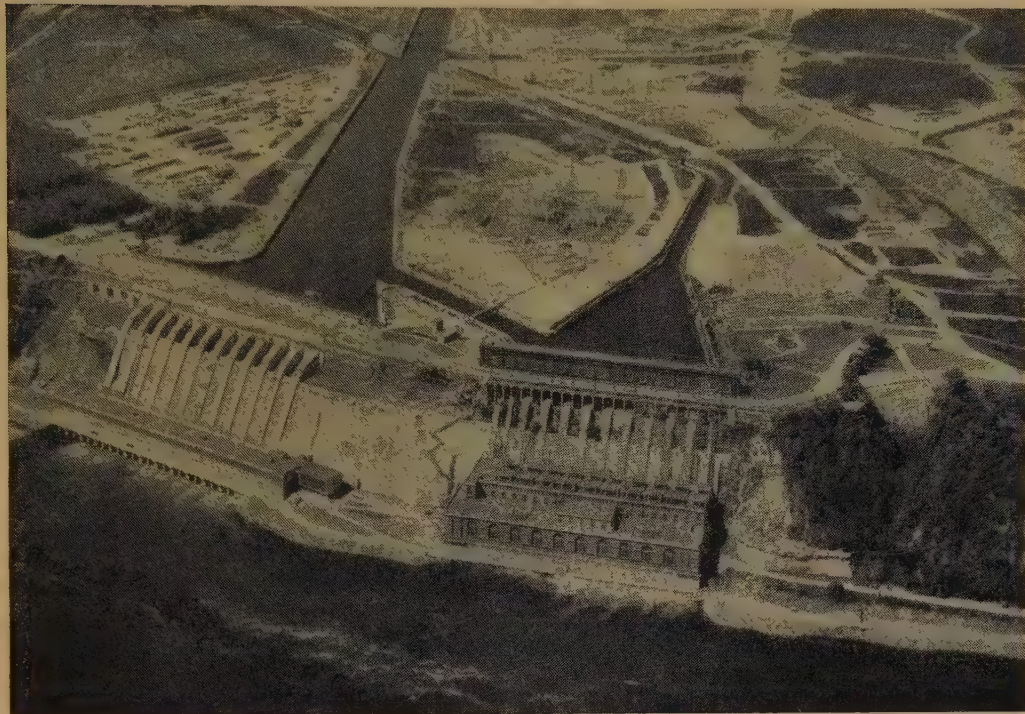


Fig. 3.—Aerial view of the Sir Adam Beck Generating Stations (No. 2 is on the left), showing the old and new canals and forebays.

and debris to a great depth. Some 35 years ago this gorge was completely filled with spoil excavated from the canal for the No. 1 plant. The gorge crossing for canal No. 2 is similar to that used for canal No. 1. It was considered inadvisable to cross the gorge with the tunnels, and for this reason, among others, the exit portals are placed to the south so that the water would be taken across by the open-cut canal.

The section of canal crossing the gorge is 2 200 ft in length, trapezoidal in section, with a bottom width of 94 ft and side slopes of two horizontal to one vertical. The bed and slopes of the excavation were paved with a layer of crushed rock on which was placed a heavy concrete lining extending several feet above the normal operating water level. Provision is made for drainage into the canal of water in the rockfill, through suitably designed ports in the lining, should the water level be drawn down rapidly. After passing through a transition from the trapezoidal section, the canal enters a rectangular rock cut extending from the north side of the old gorge to the forebay. This part of the canal is roughly 200 ft wide with close-drilled sides. It is unlined.

A smooth bed was secured by following the natural cleavage planes of the rock strata, which are nearly horizontal. Gradual changes in width and depth are made, as necessary, to maintain a constant cross-section while conforming to the natural southerly dip of the strata. For the sides, satisfactory results were secured by means of a drilling pattern carefully worked out by the Commission's Construction Division. Very little overbreak occurred beyond the drilling line, and the general alignment of the sides is excellent. The total length of the open canal, including the trapezoidal section, is $2\frac{1}{4}$ miles.

As the new canal approaches the forebay it is necessary for it to cross the canal serving the No. 1 plant, and the plan selected from a variety of proposals to effect a crossing forms an interesting feature of the project. Details of the design were worked out in a model of the adjacent portions of the two canals.

The canal cross-over model was perhaps the most interesting and most productive of savings in construction cost and effort of all the models tested. The location of the new Sir Adam Beck–Niagara Generating Station No. 2 was upstream from the No. 1 plant, as shown in Fig. 3, and a direct line from the tunnel outlet to the new plant crossed the old power canal at an angle of about 32°. If the new canal could proceed on this line and cross the old canal at the same grade and water level, then very substantial savings would result. The alternative would be a costly inverted siphon under the old canal, or a costly circuitous route from the new canal via the old No. 1 plant forebay.

The crossing of the old canal—48 ft wide and with velocities up to about 15 ft/sec—with the new canal—200 ft wide with velocities up to about 7 ft/sec—at the same grade of water level and without a large energy loss appeared to be a most formidable design problem, but when tested in a model it soon became apparent that the crossing, or intersection, was actually a merging and redistribution area, and a simple solution was found to achieve this distribution efficiently. First the old canal was gradually widened as it approached the crossing, so that its velocity was efficiently reduced to about that of the new canal when they merged. Next, the centre-line of the new canal, downstream from the crossing, was offset by 45 ft (this is clearly visible in Fig. 3); by this offset, area was provided for the old canal flow to proceed smoothly into the new canal, and at the same time, a portion of the flow approaching in the new canal was deflected into the downstream leg of the old canal. Offsetting the centre-line was the major discovery of the tests. If more flow was to be deflected into the old canal, the offset would be proportionately increased. The required amount of offset was found to be proportional to the amount of flow interchange. Careful observations in the model indicated that no appreciable energy loss beyond that of normal channel friction occurred in the cross-over.

As the canal emerges into the forebay, further widening takes place and the velocity is gradually reduced until at the headworks it is about 3 ft/sec; before the headworks are reached an interconnecting canal, 100 ft wide and 700 ft long, between the forebays leads off to the left.

An interesting feature of the canal and forebay construction

was the method used to blast the final plug of rock, left until all other work was completed in the new forebay. Throughout the period of construction of the new project, plant No. 1 was maintained in full service. Because water is non-compressible and would transmit the shock of the blast directly to the headworks of the No. 1 plant, the obvious procedure would have been to close down the generators, drain No. 1 forebay and blast out the obstruction in the dry. This would have entailed buying power at an estimated cost of about $1 000 000.

An explosives expert suggested the introduction of an air cushion in the forebay of the No. 1 powerhouse to dissipate the waves of concussion set up by the detonation. Tests made on models indicated that this sort of scheme could be made to work, and from the information gained in these tests the necessary piping was laid out to produce the desired damping effect.

Based on the calculations made by the engineers during their experiments, the desired cushion of bubbles was obtained by forcing compressed air at 90 lb/in^2 into the piping system at a rate of 3 750 ft^3/min, the upward rush of the churning air raising the surface of the water about 4 ft above the normal level. The installation cost amounted to some $2 000.

(6) FOREBAY AND HEADWORKS

After the crossing of the two canals, the water enters the final half-mile of rectangular canal and passes into the forebay. The shape of the new forebay differs substantially from that for the No. 1 plant, for it was found after the construction of the old forebay that the water was eddying at the sides. Tests on the original No. 2 forebay design indicated that the flow would not expand at the rate provided, and serious back eddies occurred. After intensive tests the original design was modified to provide the maximum expansion that the water would follow, and the walls of the forebay actually traced the streamline for maximum expansion. The interconnecting canal was placed so that all its area would be effective, and it was found that its width could be reduced from that originally planned. The design of the forebay and interconnecting canal eliminated all back eddies and all area was effective. In so doing, a saving of some $800 000 was made possible compared to the original design.

At the downstream end of the forebay the new headworks, consisting of an 875 ft-long concrete structure, runs the entire width of the forebay. It is here that control of the water entering the penstocks is maintained. There are 32 openings on the upstream side of the headworks, two for each of the 12 penstocks presently installed and for the four future penstocks, and each pair of openings converges into one inside the structure. In the concrete piers there are three sets of steel-lined gains or checks. The upstream checks house trashracks for screening debris from the water. The next set houses the stop-log gates which are used to dewater the headworks for maintenance of the main gates, located immediately behind them. The main gates are of steel construction of the fixed-roller type and are operated by electric-motor-driven hoists situated in the gatehouse, a modest structure built integral with the headworks. A 25-ton travelling gantry crane runs above the gatehouse and is used to raise and lower the screens and stop-log gates.

(7) THE PENSTOCKS

Twelve penstocks have been installed, one for each unit, with provision for four more when the balance of the 16 generating units are installed. The penstocks are 19 ft in diameter and about 500 ft long, of welded-steel construction with the plate thickness varying from $\frac{5}{8}$ in at the top to $1\frac{1}{2}$ in at the lower end. Each penstock was built of 68 prefabricated rings and brought to the site by road. They were lowered down the cliff on rails built on the penstock saddles installed in shallow trenches cut in the face of the cliff, on a slope 60° from the horizontal for the greater part of their length. To ensure a perfect joint, each weld was X-rayed and the penstocks were then encased in 2 ft of concrete to protect them from rapid and extreme temperature variations.

(8) THE POWERHOUSE

The generating station is located on the river bank in the gorge a few hundred feet upstream from the No. 1 powerhouse (see Fig. 3), and in many respects it exemplifies the progress that has taken place since the earlier station was built. The building itself is an impressive structure of pleasing architectural design, at present 930 ft long to house 12 generating units; later it will be extended to 1 150 ft to accommodate four additional units. It is 63 ft wide, 50 ft high and of rigid-frame steel construction with reinforced-concrete walls and roof. At the downstream end is the control room, which will eventually house the control instruments for both the No. 1 and No. 2 plants as well as those for the pumping generating station.

Elbow-type draught tubes are used to return the water to the river after it has given up its power to the Francis-type turbines. These tubes were constructed by using wooden forms built locally and transported to the powerhouse site by motor float. The forms were set in an excavation at the base of the powerhouse, 42 ft below the river surface, behind the cofferdam. Concrete was then poured around them and the wooden forms were removed when the concrete had finally set. The draught tubes are circular at the upper end to fit the discharge end of the turbine; they then make a right-angle bend transitioning to a rectangular section within the base of the powerhouse, emerging on the river side to discharge the water.

On the concrete slabs forming the draught-tube roofs are set the scroll cases which house the turbines. The steel plate-lined scroll cases emerge from the back wall with a 19 ft diameter at the base of the penstocks, diminishing in diameter to zero at the end of the scroll where they meet the turbines. This ensures uniform water supply around the speed rings and places equal pressure on all blades of the turbines.

The 12 turbines have a rated capacity of 105 000 h.p. each under a head of 292 ft, and rotate at 150 r.p.m. They are equipped with Woodward actuator-type governors, a single cabinet housing the actuators for two adjacent units. The turbines are spaced on 55 ft centres and are directly connected to vertical-shaft generators.

Gibson tests completed on all 12 turbine units show high efficiencies, maxima ranging between 92·4 and 94·5%; all showed a maximum output slightly exceeding 110 000 h.p. at rated head with high efficiency extending over a wide range of their capacity.

Each generator is rated at 80·5 MVA, 95% power factor, 3-phase 60 c/s and 13·8 kV. Each is totally enclosed, air-circulation-water cooled, with non-continuous amortisseur windings, and has a direct-connected exciter and static voltage regulator. Six are of the conventional type with thrust bearings above the generator, and six are of the umbrella type with thrust bearings below the rotor. The generators are below the operating floor of the powerhouse, with only the exciters and governor cabinets extending above this level.

The main transformers, which increase the generator voltage from 13·8 to 230 kV, are located on a deck immediately behind the powerhouse superstructure. One bank of three single-phase 62 MVA transformers is provided for each pair of generating units, the output of which is carried to the transformers through a 5 kA air-blast circuit-breaker and a copper metalclad busbar. The high-voltage circuits from the transformers are carried on

steel towers and girders, mounted on the penstock envelopes, to the top of the escarpment, and from there across to the switchyard located on the island between the two forebays; this is clearly visible in Fig. 3.

(9) THE SWITCHYARD

The 230 kV switching structure can be described diagrammatically as a large ring busbar with two diameters. There are at present five outgoing lines which feed into the Commission's system at various switching and transforming stations, and one which interconnects the Ontario Hydro-Electric network with the Niagara–Mohawk Power Corporation network in the State of New York, across the Niagara River.

The 230 kV circuit-breakers are of two different types, both built in Canada; there are six type FK439, conventional, round-tank units and seven type FGK units which have flattened lenticular tanks and require somewhat less oil but have identical mechanisms and interrupters to those in the FK439. These circuit-breakers are rated at 1·2 kA, have an interrupting capacity of 10 000 MVA and an interrupting time of 3 cycles. The last FGK circuit-breaker, which is now in one of the Niagara–Mohawk line positions, is of slightly modified design and is rated at 15 000 MVA; this was an advance in design made after the purchase of the earlier units.

Currents for metering and protective devices are taken from current transformers mounted on the circuit-breaker bushings, while voltages are provided by coupling capacitor devices. Special high-accuracy current transformers and 230 kV voltage transformers were installed for billing purposes on the Niagara–Mohawk line. Isolation of the various 230 kV equipment is provided by disconnecting switches, those in the transformer circuits and lines being motor operated and those on each side of each circuit-breaker being manually operated. The conductors in the switching structure are 10^6 circular-mil hollow-core copper in all strains and drops and 2 in-bore copper tube in all rigid busbar sections. There are three levels, the lowest, at about 20 ft above grade, being rigid, and the others, at 40 and 60 ft, being strained. The whole structure is protected by overhead earth wires and a mat of buried conductors interconnecting all steel structures and equipment. Conical spark-gaps at the line entrances protect against lightning surges coming in on the lines.

(10) PUMPED-STORAGE DEVELOPMENT

The pumping-generating station (Fig. 4) is designed as an adjunct to the main station to use any surplus energy during night hours for pumping water under low head into a reservoir, whence it can be drawn to generate primary energy under high head in daytime periods of high demand. The pumped-storage scheme consists essentially of a canal to connect into the present canal system, the pumping-generating station and an artificially created reservoir.

The pumped-storage canal is essentially a reversible-flow channel, which conveys water from the main canal during the pumping cycle in which the reservoir is being filled and discharges it back when storage is being withdrawn to increase load at the main plants. The canal is approximately 1 450 ft long and has a normal width of 140 ft, with a flaring section about 650 ft long to conform with the length of the pumphouse. The average depth of rock cut was 58 ft, with a maximum at the pumphouse end of 80 ft. About 20 ft of overburden covered the rock.

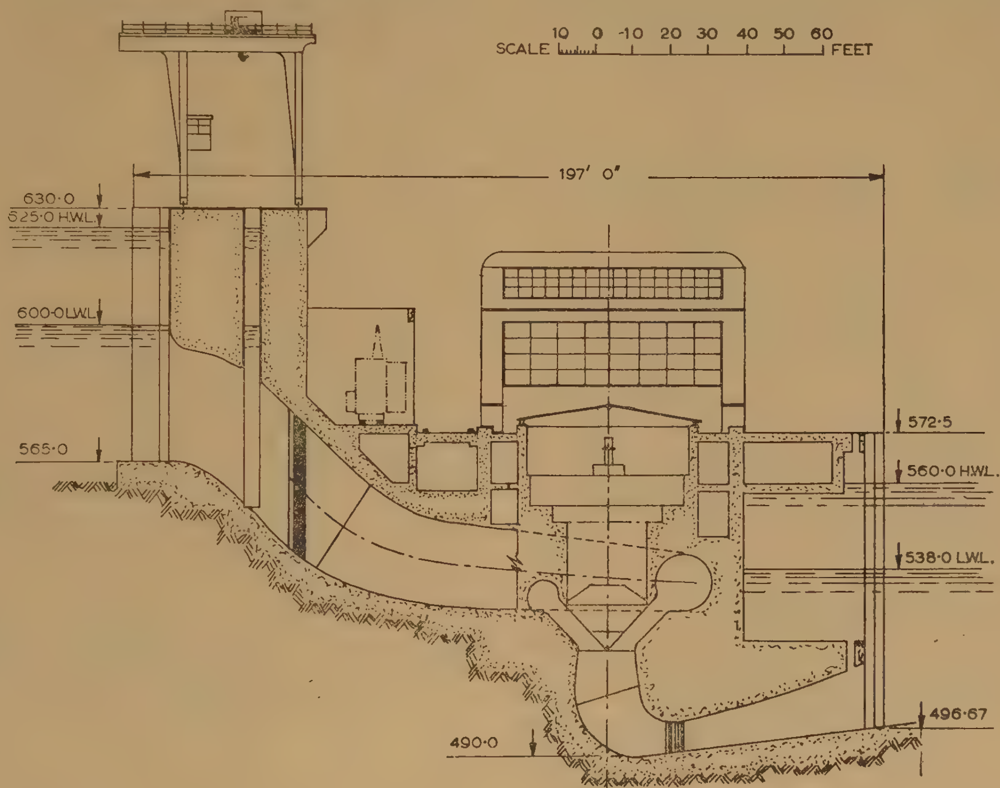


Fig. 4.—Cross-section of the pumping-generating station for the pumped-storage scheme.

During the pumping cycle the normal depth of water in the canal will be about 23 ft and the velocity $8\frac{1}{2}$ ft/sec. During the generating cycle the depth will be about 26 ft and the average velocity about $6\frac{1}{4}$ ft/sec with the turbines operating at the best gate.

The pumped-storage reservoir is an artificial lake about two miles long and one mile wide; it has an area of 750 acres and, on the basis of 25 ft of drawdown, will provide usable storage of about 15 500 acre-ft. The reservoir is formed by an embankment, essentially a rockfill mass supporting an impervious clay core for watertightness; this type was chosen because clay deposits were available in the vicinity and the rockfill could be obtained economically from the canal excavation. The rock in the bottom of the reservoir is generally covered with overburden in variable depth, consisting of impervious layers of silt and clay. However, in locations where the overburden has been eroded, or where insufficient overburden or creek beds exist, additional clay will be placed to provide watertightness. In effect, a continuous membrane of clay is provided throughout the entire reservoir area.

The dyke varies in height from 15 to 65 ft and has a total length of about 24 300 ft. It involves the placement of 1 300 000 yd^3 of rockfill, 800 000 yd^3 of filter material and 650 000 yd^3 of compacted clay for the impervious central core. In operation, the normal high water will be at elevation 625 and the low at elevation 600. Since the ground elevation within the reservoir area ranges from about 615 to 570, less than half the enclosed area will be submerged at minimum water level.

The equipment to be installed in the pumping-generating station consists of six reversible feathering-blade Francis-type pump-turbines each direct-connected to a motor-generator. Operating as pumps these units will discharge 4 000–5 000 ft^3/sec under a variable head ranging from 90 to 60 ft respectively; for this condition the motor is rated 55 000 h.p. With this equipment it will be possible to fill the reservoir in about $7\frac{1}{2}$ hours.

As turbines, these units are rated at 40 500 h.p. under a head of 80 ft, and the discharge will vary between 5 600 and 4 100 ft^3/sec with a head range of 80–38 ft (speed, 92·3 r.p.m.). If desired, the turbines may be operated to give a constant discharge of about 4 100 ft^3/sec over the full head range.

The power plant consists of a massive concrete headworks structure and the powerhouse itself, which is directly downstream from and integral with the headworks structure. This structure, together with a short concrete gravity section at the west end, forms a dam section between the ends of the enclosing reservoir dykes.

The distance from the face of the headworks to the end of the draught tube is about 125 ft and the overall length of the powerhouse is 452 ft. An erection bay about 120 ft long is provided at one end for servicing the units. The units in this plant are on 74 ft centres and are the largest in physical size to date in the Ontario Hydro-Electric Commission's system, although this will be exceeded at the St. Lawrence project, where the centre-to-centre distance will be 80 ft.

The headworks is somewhat similar to that of the No. 2 plant. It contains the conventional trashracks and steel headgates, which may be closed by remote control in an emergency. A 50-ton headworks gantry is provided for removal of racks and gates.

The pumping-generating station is a modified outdoor type and is the first of its kind to be constructed by the Ontario Hydro-Electric Commission. This type of powerhouse was first introduced in the southern part of the United States, but in recent years similar plants have been constructed in Quebec, where climatic conditions are more rigorous than those encountered in the Niagara area. A saving of about $2 000 000 has been effected by the elimination of the conventional superstructure which normally provides the enclosure for the generating units.

The pump-turbines to be installed at this plant are of particular interest and are a new development in the field. The runner is of the diagonal-flow type with eight movable trunnion-supported blades sloping downwards at an angle of 45° from the runner hub. The blade angle is adjusted by a vane-type servo motor located in the runner hub. The hub and inner edges of the blade are finished spherical, permitting unrestricted feathering of the blades and also close clearance tolerances. Similarly, the outer edges of the blades and the throat-ring wall are spherical. Because of the close clearance between the hub, the blade edges and the throat ring, the blades in the closed position form a reasonably watertight closure and the conventional wicket gates and their operating mechanism have been eliminated. When the machine is shut down, additional thrust may be introduced on the top of the runner hub by closing the headcover drain valve, which produces a deflection and reduces the clearance between ends of the blades and the throat ring. This reduces blade-gap leakage to a minimum. The steel-plate casing is set well above the centre of the blades to ensure axial flow past the blades.

When acting as a pump, the unit is started with the blades in the closed position and is brought up to speed without the necessity of depressing the water level in the draught tube. This requires very little effort other than the inertia of the runner and motor, and starting will consequently be across the line, with an expected surge current about 250% of running current. When synchronous speed has been attained the blades will be gradually opened and the pumping cycle will begin.

The units will be operated at 13·8 kV with transformation directly to 230 kV and will be connected to the system at the present switchyard. When operating in the reverse direction, the main leads and such other controls and protective circuits as are necessary will be reversed.

(11) CONCLUSION

Her Royal Highness the Duchess of Kent graciously consented to open the Sir Adam Beck–Niagara Generating Station No. 2 on the 30th August, 1954, and one year later the first stage, incorporating 12 units, was in full operation. Because of the unusually high rate of load growth being experienced on the Commission's system, it was announced in January, 1956, that work would commence immediately on the balance of the units. Thus, by 1958 the entire project, including the pumping-generating station, will be completed at a total approved cost of $343 742 000.

621.313.1 : 621.68

Paper No. 2111 U
July 1956

CONDUCTION AND INDUCTION PUMPS FOR LIQUID METALS

By L. R. BLAKE, Ph.D., B.Sc., Associate Member.

(*The paper was first received* 14*th October*, 1955, *and in revised form* 26*th January*, 1956. *It was published in July*, 1956, *and was read before* THE INSTITUTION 25*th October*, 1956, *at a meeting held in conjunction with the* BRITISH NUCLEAR ENERGY CONFERENCE, *the* NORTH-WESTERN CENTRE 6*th November and the* NORTH-EASTERN CENTRE 10*th December*, 1956, *and the* RUGBY SUB-CENTRE 30*th January*, 1957.)

SUMMARY

Two main types of electromagnetic pump for liquid metals can be distinguished: conduction pumps, a.c. or d.c., in which a magnetic field is established across a tube containing liquid metal, and current is fed to the liquid through electrodes connected to the tube walls; and induction pumps, in which a travelling field induces the required current, as in the induction motor. The induction pump takes three main forms: annular linear (Alip), flat linear (Flip), and spiral (Sip). These are probably the most useful types of electromagnetic pump for liquid metal, and each is examined and compared in an attempt to predict their relative performance and their main design features.

LIST OF PRINCIPAL SYMBOLS

Co-ordinates and Dimensions.

x = Co-ordinate in main direction of magnetic field, cm.
y = Co-ordinate in main direction of current flow, cm.
z = Co-ordinate in main direction of liquid flow, cm.
t = Time, sec.
a = Width of tube (internal) in x-direction, cm.
b = Width of tube (internal) in y-direction, cm.
c = Overall effective length of pump in z-direction, cm.
λ = Wavelength of field (twice pole pitch), cm.
w = Thickness of tube wall (w_i = inner; w_o = outer), cm.
d = Magnetic gap-width in x-direction, cm.
$\psi = 2\pi z/\lambda$.
D, C = Diameter and mean circumference, respectively, of a spiral induction pump, cm.

Properties of Materials.

ρ = Resistivity of liquid metal, ohm-cm.
σ = Density of liquid metal, gm/cm^3.
ρ_t = Resistivity of tube material, ohm-cm.
σ_t = Density of tube material, gm/cm^3.
μ = Viscosity of liquid metal, poise.

Pump Performance Data.

p = Gross pressure developed by pump (main component p_z), dynes/cm^2.
p_h = Hydraulic pressure drop in pump, dynes/cm^2.
q = Flow, cm^3/sec.
P_0 = Pump output power ($pq/10^7$), watts.
P_h = Hydraulic friction loss in tube, watts.
$P_0' = P_0 + P_h$, gross output power, watts.
P_f = Ohmic loss in fluid, watts.
P_t = Ohmic loss in tube walls, watts.
P_w = Ohmic loss in winding, watts.
η_i = Ideal-pump efficiency, $P_0'/(P_0' + P_f)$.
η = Overall pump efficiency $(P_0' - P_h)$/(total input power).

Pump Design Data.

J_f = Current density in fluid (main component J_y), amp/cm^2.
J_t = Current density in tube walls, amp/cm^2.
J_p, J_m = Peak and mean values, respectively, of current density in fluid, amp/cm^2.
H = Field in liquid metal (main component H_x), oersteds.
H_p, H_m = Peak and mean values, respectively, of field, oersteds.
Φ = Total flux, maxwells.
f, ω = Frequency and angular frequency, c/s and rad/sec.
v = Velocity of liquid in tube, cm/sec.
v_s = Synchronous velocity in an induction pump, cm/sec.
s = Slip, $(v_s - v)/v_s$.
V, I, R, Z = Voltage, current, resistance, impedance generally.
V_i = Induced voltage, volts.
N = Number of turns.
NI = M.M.F. $\times 10/4\pi$, ampere-turns.
m = Number of slots per phase per pole.
k_{d1} = Winding distribution factor, $\frac{1}{2}m \sin(30°/m)$.
δ = Spiral angle in spiral induction pump.
n_1 = Number of pole pairs in spiral induction pump.
n_2 = Number of spirals in spiral induction pump.

Parameters.

$P_\lambda = ab\lambda H_p^2 v_s^2/2 \times 10^{16}\rho$, induction-pump power parameter.
$H_i = 2\pi J_m c/10$, a parameter representing the maximum field produced by the current in a conduction pump.
$\beta = 2\pi vc/10^9\rho$, a parameter upon which depends the amount of distortion of the current density in a conduction pump.
$h = 2v_s s\lambda/10^9\rho$, parameter controlling flux penetration in the induction pump.

$$k_{t1} = \frac{w_i + w_o}{a}\frac{\rho}{\rho_t}.$$

(1) INTRODUCTION

Conventional mechanical methods of pumping present special difficulties with liquid metals, particularly in making the glands, seals and bearings completely effective, yet reliable and easy to maintain. On the other hand, the high conductivity of liquid metal permits the use of electromagnetic pumps, which utilize the pressure developed within the liquid itself when carrying current in the presence of a magnetic field. Although electromagnetic pumps are sometimes lower in efficiency, they are often smaller in size and are likely to prove more reliable and require less routine maintenance than mechanical pumps, for with them the liquid metal can be sealed off completely within pipes. An accurate picture of how the two methods compete with and complement each other with different metals and at differing power levels will undoubtedly take some time to emerge.

Sodium, sodium–potassium and bismuth are three of the most important liquid metals. Sodium and sodium–potassium are particularly useful in high-temperature applications where a high

Dr. Blake was formerly at the Research Laboratory of the British Thomson-Houston Co., Ltd., and is now with the United Kingdom Atomic Energy Authority (Research and Development Branch).

rate of heat transfer of up to several kilowatts per square inch is required, as in a fast reactor. The main interest in bismuth is not so much for its heat-transfer properties as for its use in liquid-fuel reactors, since it has the ability to dissolve uranium and possesses a low neutron-absorption cross-section. Sodium has better pumping properties in all respects than bismuth, with appreciably lower values of resistivity, viscosity and density. A low resistivity is desirable for low ohmic loss and high efficiency, and to permit induction methods of pumping; low density and viscosity enable a high fluid velocity to be employed, giving smaller magnetic-gap distances, improved efficiency and smaller pump size.

(1.1) Types of Electromagnetic Pump

The electromagnetic pump operates on the same principle as the electric motor, as symbolized by Fleming's left-hand rule. Successful operation depends, therefore, on obtaining simultaneously in the liquid a current and a magnetic field perpendicular to each other and to the required direction of fluid flow. There are many types of electromagnetic pump, just as there are many types of electric motor, and pumps and motors are often directly analogous in their function. Pumps can be conveniently divided, however, into two main groups: conduction types, in which current is fed to the liquid metal from an external source; and induction types, where the current is induced either by the main or by an auxiliary magnetic field which can be of pulsating or travelling-wave type.

Fig. 1 shows a simple arrangement of conduction pump in

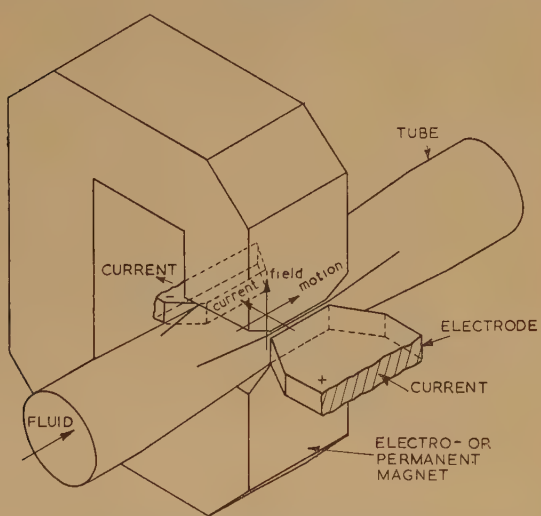


Fig. 1.—Conduction pump in its simplest form.

which a field is established across the tube containing the liquid metal, and current is fed to it through electrodes connected to the tube walls. Spiral or helical forms of this pump are useful in high-pressure low-flow applications. The large electrode current requirements and large busbar sections, which are the chief disadvantages of both a.c. and d.c. conduction pumps, can be avoided by inducing the current in the liquid metal; one of the most convenient methods of doing this is to employ travelling waves of flux, as in the induction motor. The spiral induction pump (Sip) (Fig. 2) most closely resembles the induction motor in appearance and operation. Here the liquid is deflected by vanes to give it a spiral motion, the action of the field producing circumferential motion.

Linear induction pumps can also be made which avoid the spiral motion of the liquid: the flat linear induction pump (Flip)

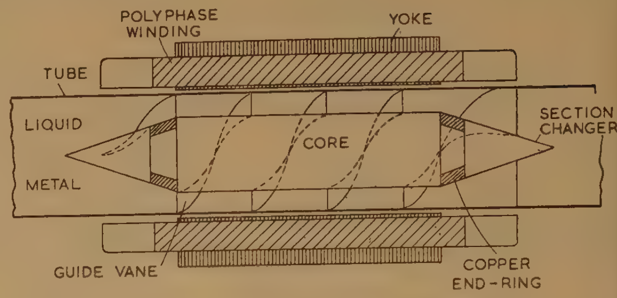


Fig. 2.—Spiral induction pump (Sip).

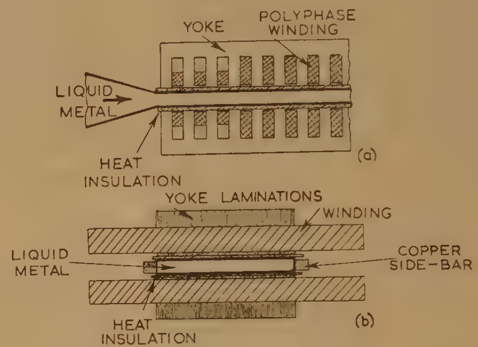


Fig. 3.—Flat linear induction pump (Flip).
(*a*) Longitudinal. (*b*) Transverse sections.

has a flat winding arranged in line (Fig. 3). Side bars of copper fixed to the tube walls perform the function of the end rings in the Sip or induction motor. The annular linear induction pump (Alip) (Fig. 4) is a further form in which an annular space is left

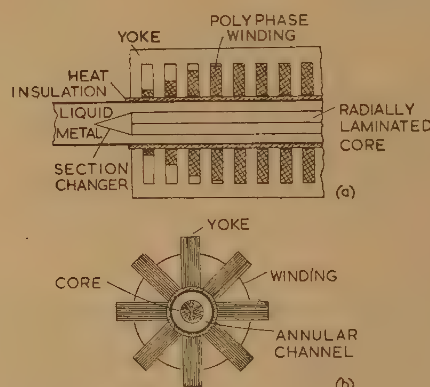


Fig. 4.—Annular linear induction pump (Alip).
(*a*) Longitudinal. (*b*) Transverse sections.

for the liquid metal between the central magnetic core and the outer winding, which takes the form of separate rings spaced along the tube. Other forms of this pump, which permit the winding to be removed without disturbing the pipework, are the split-winding arrangement, which is virtually a cross between the Flip and the Alip, and the reverse-flow Alip, in which the liquid metal enters the pump in a circular pipe within the central magnetic core and reverses direction at the end of the pump, flowing then in the annular space between the core and the winding. General descriptions of electromagnetic pumps are given in References 10–13.

(1.2) Basic Equations of the Electromagnetic Pump

Consider an element of sides dx, dy and dz (Fig. 5), where the rrent density is J_y and the field H_x. Equating forces acting the element in the direction z, we obtain

$$\frac{\partial p_z}{\partial z} = \frac{J_y H_x}{10} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

ere are similar expressions for the x- and y-components of

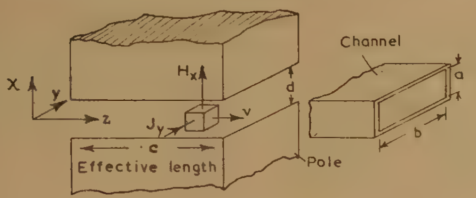


Fig. 5.—Quantities involved in analysis of pump.

essure at position (x, y, z). The total pressure developed in a mp of effective length c is

$$p_z = \int_0^c \frac{J_y H_x}{10} dz \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

the pressure is uniform across the tube in the x- and y-directions, e gross output power is

$$P'_0 = p_z q/10^7 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

ere q is the flow ($=vab$). The ohmic loss in the fluid, again suming uniformity, is

$$P_f = ab\rho \int_0^c J_y^2 dz \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

J_y and H_x vary with time, so also do p_z, P'_0 and P_f.

These expressions are basic to all forms of electromagnetic mp and will be employed later when considering conduction d induction pumps in detail. Other losses in addition to P_f clude the hydraulic friction loss, P_h, which has common atures in all forms of pump and will be examined briefly the next section, winding loss, P_w, losses in the tube walls, P_t, dy-current losses, core losses, and so on, and in addition there n be other substantial and perhaps unexpected losses as will seen later.

(1.3) Hydraulic Losses in Electromagnetic Pumps

The normal methods of calculating hydraulic friction losses e of limited applicability in the electromagnetic pump since the nductivity of liquid metals is high and since flow takes place a magnetic field. Generally, the effect of turbulent motion is induce electric currents which react with the magnetic field d produce forces resisting motion; as a consequence the draulic loss is increased and the region of streamline flow is tended to unusually high values of Reynolds number.

It is usual in fluid-flow calculations to employ the fluid friction ctor C_f, defined by $C_f = \tau_0/(\frac{1}{2}\sigma v^2)$, where τ_0 is the wall shear ress, σ the density of the fluid, and v the mean velocity. By uating the total shear force on the walls to the total pressure op, it follows that for the round pipe, the pressure drop is $hg\sigma$ or $4\tau_0 l/d$, and for the wide rectangular tube with walls istant a apart, p is $2\tau_0 l/a$. Substituting for τ_0 leads to the ell-known expression for the round pipe for the head loss due to friction, $h = 2C_f lv^2/gd$, and for the rectangular tube $h = C_f lv^2/ga$.

For smooth circular pipes, the friction factor C_f under turbulent-flow conditions (i.e. for Reynolds number $R > 4000$, where $R = \sigma vd/\mu$, and σ, μ are the density and viscosity respectively) is given (among many others) by an expression due to Prandtl:

$$1/\sqrt{C_f} = 4 \log (2R\sqrt{C_f}) - 1{\cdot}6 \quad . \quad . \quad . \quad (5)$$

It is also reasonably accurate for other pipe sections, provided that in the expression for R the equivalent diameter is written as $4 \times$ (pipe area)/(pipe periphery). Thus for the wide rectangular tube, $R = 2\sigma av/\mu$, and eqn. (5) can be applied in estimating the losses under turbulent-flow conditions.

J. Hartmann and F. Lazarus[2] have investigated the effect of a magnetic field on the hydraulic loss for the case of mercury flowing in a rectangular channel, and their work has been extended by W. Murgatroyd.[3] It is shown that, if in the absence of a field the flow is turbulent, as the magnetic field is increased, turbulence is gradually suppressed and Cj gradually increases, although it may decrease at first. A theoretical expression (Hartmann) for C_f under laminar-flow conditions is, approximately,

$$C_f = 8M/R \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where $M = \mu_m Ha/(4 \times 10^9 \mu\rho)^{1/2}$, and $R = 2\sigma va/\mu$. Here H is the field in gauss, μ_m the magnetic permeability of the fluid, and ρ the resistivity of the fluid. Other symbols are as before.

If it is assumed that the Prandtl equation can be applied to the rectangular channel and holds for low values of M, and the Hartmann equation for large values of M, then C_f can be plotted for a wide range of values of M and R. This is done in Fig. 6.

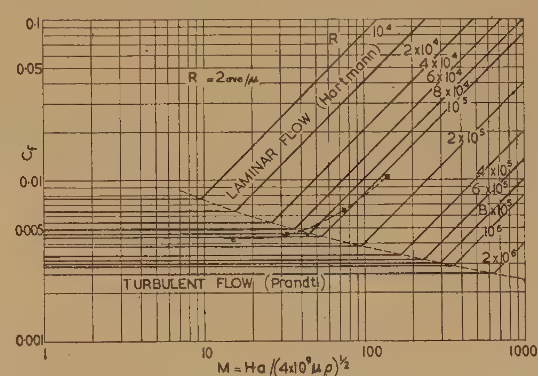


Fig. 6.—Dependence of the fluid friction factor on Reynolds number and M.

—■—■— Experimental results for mercury at $R = 1{\cdot}02 \times 10^5$ (Murgatroyd).

Tests by Murgatroyd using mercury over a range of values of R from 10^4 to $1{\cdot}21 \times 10^5$ generally confirm the accuracy of Fig. 6; one curve for $R = 1{\cdot}02 \times 10^5$ is indicated to give some idea of the modification to be expected at the transition between laminar and turbulent flow, which of course is not abrupt as shown. The data of Fig. 6 can be used, therefore, to determine C_f and so estimate the hydraulic losses in liquid metals flowing through channels in the presence of a magnetic field. It must be mentioned, however, that the validity of these curves has been confirmed for mercury only.

(2) THE INDUCTION PUMP

(2.1) Design Equations of the Ideal Linear Induction Pump

The design equations of the ideal forms of annular (Alip) and flat (Flip) induction pumps will be considered together by

assuming the pump to be flat and of infinite width in the y- or current-flow direction, as indicated in Fig. 7. A strip of finite width b of this infinite extent corresponds to the channel width of the Flip pump if the side electrodes are assumed perfectly conducting and to extend well beyond the pump, and to the mean circumference of the annular gap in the Alip pump. Only the x-component of H and the y-component of J will be assumed here to exist. The relation between the current density in the fluid, J_f, in the tube walls, J_t, the field, H, the core flux, Φ per unit length, the magnetizing ampere-turns, dNI_m/dz, and the induced voltage per turn, V_i/N, are derived as follows.

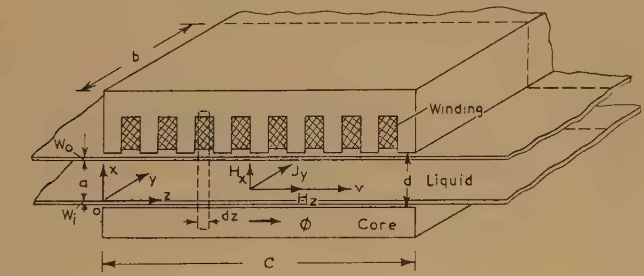


Fig. 7.—General arrangement and quantities involved in analysis of the linear induction pump.

Since lines of flux are continuous

$$\Phi_z - \Phi_0 = \int_0^z bHdz \text{ or } H = \frac{1}{b}\frac{\partial\Phi}{\partial z} \quad . \quad . \quad . \quad (7)$$

From Faraday's law (Maxwell's second equation)

$$\rho b 10^8 J_f = -\frac{d\Phi}{dt} = -\left(\frac{\partial\Phi}{\partial t} + v\frac{\partial\Phi}{\partial z}\right) \quad . \quad . \quad (8)$$

This equation assumes $J = 0$, $z = 0$ and $z = c$ for the flat pump. The current density in the tube walls, J_t, is simply derived from J_f by replacing ρ by ρ_t and putting $v = 0$. By applying Ampère's law to the circuit of width dz shown dotted,

$$\left[H - \left(H + \frac{\partial H}{\partial z}dz\right)\right]d = \frac{4\pi}{10}dNI_m$$

hence

$$\frac{dNI_m}{dz} = -\frac{10d}{4\pi}\frac{\partial H}{\partial z} = -\frac{10d}{4\pi b}\frac{\partial^2\Phi}{dz^2} \quad . \quad . \quad . \quad (9)$$

The voltage per turn induced in the winding is given by

$$\frac{V_i}{N} = \frac{d\Phi}{dt}10^{-8} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

If the flux is assumed to be of the form $\Phi = \Phi_0 \cos(\omega t - \psi)$, as in the induction motor, where $\psi = 2\pi z/\lambda$, then, from eqn. (7), $H = H_p \sin(\omega t - \psi)$, where $H_p = (2\pi/\lambda b)\Phi_0$. Similarly using eqns. (8)–(10), expressions for J_f, J_t, dNI_m/dz and V_i/N can be derived (see Appendix 6.1). If these are substituted in eqns. (1)–(4), expressions can be deduced for the pump pressure p, the gross output power P_0', and the ohmic loss in the fluid P_f and tube walls P_t. For P_0' and P_f the results are

$$P_0' = P_\lambda(1 - s)s \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

$$P_f = P_\lambda s^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

where $P_\lambda = v_s^2 ab\lambda H_p^2/(2 \times 10^{16}\rho)$ and the slip $s = (v_s - v)/v_s$. The ideal efficiency $\eta_i = P_0'/(P_0' + P_f) = (1 - s)$, which is to be expected of an ideal machine working on induction motor principles.

The equations for the ideal case (which are summarized in Appendix 6.1) are of limited validity for reasons now to be given and in fact apply to the mid-section of a linear induction pump and to the spiral induction pump of small helix angle.

(2.2) End Effects in the Linear Induction Pump

It is assumed tacitly in Section 2.1 that the flux Φ is of the form $\Phi_0 \cos(\omega t - \psi)$ over the length of the pump, $0 < z < c$, and the fact that it is zero everywhere outside these limits is ignored. If the effect of the discontinuities of the ends are now considered it is evident from eqns. (7) and (9) that infinities are produced in H and dNI_m/dz which are not possible to realize in practice. Some of the calculations of Section 2.1 will be repeated, therefore, assuming the other limiting condition that the magnetizing current distribution, dNI_m/dz, is of $\cos(\omega t - \psi)$ form over the length of the pump and is zero outside. For consistency with previous expressions say

$$\frac{dNI_m}{dz} = \frac{5dH_p}{\lambda}\cos(\omega t - \psi) \quad . \quad . \quad . \quad . \quad (13)$$

The field and flux can be obtained by integrating twice according to eqns. (9) and (7). If the boundary conditions are inserted, namely $\Phi_0 = \Phi_{2n\pi} = 0$, then we obtain

$$H = H_p \sin(\omega t - \psi) \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

$$\Phi = \Phi_0[\cos(\omega t - \psi) - \cos\omega t] \quad . \quad . \quad . \quad (15)$$

It will be seen that H and dNI_m/dz are as before but Φ is different, being supplemented by the pulsating term $\cos\omega t$. Repetition of the calculation of P_0', P_f and η_i as in Section 2.1 gives the results

$$P_0' = P_\lambda s(1 - s) \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

$$P_f = P_\lambda(1 + s^2) \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

$$\eta_i = (1 - s)\left(\frac{s}{1 + s}\right) \quad . \quad . \quad . \quad . \quad . \quad (18)$$

It follows, comparing eqns. (11), (12), (16) and (17), that the effect of the pulsating component of flux is to add a pulsating component of current in the liquid metal which performs no useful work but increases the ohmic loss by a factor $(1 + s^2)/s^2$ and lowers the efficiency by a factor $s/(1 + s)$. For example, at 50% slip, where maximum power output can be achieved, the ideal efficiency is lowered from 50% to 16·7%; at 25% slip the ideal efficiency is lowered from 75% to 15%. It is evident that these effects are much too large to be tolerated.

(2.3) Methods of Grading the Winding

There are a number of ways of gradually increasing the core flux from zero at the ends that are not difficult to achieve in practice and can substantially reduce the additional losses which can otherwise occur. A method of grading the core flux over the entire length of the pump leading to a high efficiency is

$$\Phi = \Phi_0 \sin\left(\frac{\psi}{2n}\right)\cos(\omega t - \psi)$$

where n is the number of wavelengths or $2n$ the number of poles; however, this gives a low power output and the design of the pump is excessively complicated since each coil of the winding must be designed individually. A simpler arrangement is to grade the winding over end-sections leaving a uniform mid-region where all the coils are similar. As an example, the winding for the wavelength at entry could be designed to make the flux over that region be of the form

$$\Phi = \tfrac{1}{2}\Phi_0(1 - \cos\tfrac{1}{2}\psi)\cos(\omega t - \psi) \quad . \quad . \quad . \quad (19)$$

A similar symmetrical arrangement would be adopted at the pump exit. Alternatively the pole at entry could be graded in this manner to give

$$\Phi = -\tfrac{1}{2}\Phi_0(1 - \cos\psi)\cos(\omega t - \psi) \quad . \quad . \quad (20)$$

Another method is to force the field to be of the form

$$H = \tfrac{1}{2}H_p \sin(\omega t - \psi) \quad . \quad . \quad . \quad . \quad . \quad (21)$$

over one pole at each end and the normal form $H_p \sin(\omega t - \psi)$ over the central region. It is easy to show that under these conditions also the flux at the boundary between the end and middle sections (i.e. at $z = \frac{1}{2}\lambda$ in this case) is of the form $\Phi \cos \omega t$, which is the required boundary condition for the middle sections and allows the flux there to be of the ideal form $\Phi \cos(\omega t - \psi)$.

Of the innumerable methods of grading the winding, three only will be considered here: for convenient reference they will be referred to as method A, corresponding to eqn. (19); method B to eqn. (20); and method C to eqn. (21). In general method A is suitable for Alip pumps of fairly large size, where the ohmic loss in the fluid, P_f, is the predominant loss and it is desired to keep it low by operating at a low slip; method B is sometimes useful for smaller Alip pumps; and method C for Flip and split-winding Alip pumps, where it approximates to the case of half-wound end poles.

The expressions for H, Φ, J_f, J_t, dNI_m/dz, V_i/N, P_0', P_f and P_t applicable to the end sections can be derived as before. The results are given in Appendix 6.1, where they can be compared with the results for the uniform mid-section as described in Section 2.1.

The pump output and the ideal efficiency are shown plotted in Fig. 8 for the case of an 8-pole pump for the three methods of

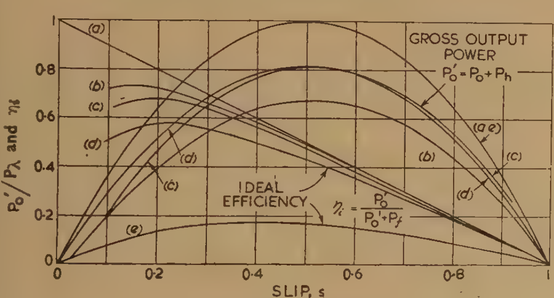


Fig. 8.—Variation of gross output power and ideal efficiency with slip for an 8-pole pump.

(*a*) Having no-end effects and with an ideal performance;
(*b*) Graded as Method A.
(*c*) Graded as Method B.
(*d*) Graded as Method C.
(*e*) Having no end-compensation.

end grading, and they are compared with the performance of an ideal pump, as in Section 2.1, and with a pump which has no end compensation winding, as in Section 2.2. It is seen that in all cases maximum power occurs close to 50% slip, but maximum efficiency occurs at appreciably lower values. Of the two practical forms of pump, the gently graded method A gives the higher efficiency and the stepped method C the higher output power. Method B is intermediate. It is possible to achieve a higher ideal efficiency than 74%, the maximum for the 8-pole pump graded by method A, by grading the winding over the entire length of the pump or by increasing the number of mid-sections.

The design of a pump with accurately graded end-sections can be very laborious, particularly when the number of slots per pole is large. With 6 slots per pole, for example, graded by method A, it is necessary to design 25 different coils: 12 for the inlet section, 12 for the outlet section (which are not similar to those at inlet unless both coil leakage reactance and resistance are negligible), and one for coils in the mid-sections. Thus the complete design of the pump is quite involved. This feature alone encourages the use of method B rather than method A in small pumps, since the number of different coils to be designed and constructed is smaller; but too abrupt grading is not without its problem, since it can lead to overheating of some of the end-winding coils, owing to the increase of the m.m.f.

(2.4) Winding Design

The total current in the winding includes the magnetizing component dNI_m/dz already derived and components which by transformer action cancel the magnetic effects of the current in the liquid and tube walls. The liquid-metal current component is $dNI_L/dz = -J_f a$, and the tube-wall current component is $-(k_{t1}/s)J_f a$. Thus, the ideal distribution of winding current is the vector sum

$$\frac{dNI_T}{dz} = \frac{dNI_m}{dz} + \frac{dNI_L}{dz}\left(1 + \frac{k_{t1}}{s}\right) \quad . \quad . \quad . \quad (22)$$

For a 3-phase winding with m coils (or bars) per phase per pole and one coil (or bar) per slot, the total coil current-turns at position z are

$$NI_T = \frac{\pi}{3}\int_{z-\lambda/12m}^{z+\lambda/12m} \frac{dNI_T}{dz}dz \quad . \quad . \quad . \quad . \quad . \quad (23)$$

The factor $\pi/3$ is inserted to give agreement with the more complete analysis of a 3-phase winding[4] and would tend to unity as the number of phases increased. For the mid-section coils eqn. (23) can be written

$$NI_T = \frac{\lambda}{6mk_{d1}}\left(\frac{dNI_T}{dz}\right)_z \quad . \quad . \quad . \quad . \quad (24)$$

where k_{d1} has the same form as the winding distribution factor, that is, $k_{d1} = (1/2m)\sin(30°/m)$. The voltage per turn required to excite the coil is

$$\frac{V}{N} = \left(\frac{\partial\Phi}{\partial t}\right)_z 10^{-8} + (NI_T)_z\left(\frac{Z}{N^2}\right) \quad . \quad . \quad (25)$$

where Z is the coil impedance (leakage reactance and resistance), calculated as in other electrical machines. Eqns. (22), (23) and (25) can be applied when designing the coils for both mid- and end-sections by substituting the appropriate equations of Sections 2.1 and 2.3. Calculation of the coil ampere-turns by the method of eqn. (23) is slightly unorthodox, but is suggested since it applies equally to end- and mid-section coils.

(2.5) Flux Penetration in the Induction Pump

It is often desirable to employ a large channel width a in a large pump, but this leads to a large value of a/λ, since λ increases little as the size of a pump is increased. This is because the slip s tends to decrease with size, and although the permissible fluid velocity v increases, the synchronous velocity $v_s = v/(1 - s)$ remains virtually unchanged; thus if the frequency is constant, $\lambda = v_s/f$ is also virtually independent of the size of the pump. The use of a large value of a/λ is liable to create difficulties due to limited flux penetration, so it is desirable to examine these effects.

So far, it has been assumed that the field crosses the gap perpendicularly so that the H_y- and H_z-components are absent. The assumption that H_y is zero is reasonable, but it is definitely approximate to assume H_z is zero; this is equivalent to ignoring

flux penetration effects or, in other words, the reactive impedance to current flow in the liquid metal. A more accurate picture of the field in the gap shows H_x increasing as the winding is approached, and H_z also increasing from zero at the core to an appreciable value on the winding side of the gap. The field variation within the liquid alters the pressure distribution, making p_z low on the core side and also introducing a component p_x, due to the interaction of J_y and H_z; this in turn makes the fluid velocity v_z vary across the gap and introduces a v_x-component. Exact calculation of these effects is complicated, but useful results can be obtained assuming the H_z-component of field to be present in addition to H_x, the velocity uniform of value v, and the v_x-component absent.

Assume, therefore, that the liquid velocity v is constant, and that the components of H and J exist in the following form:

$$H_x = \mathscr{R} H_1 \varepsilon^{j\omega(t-z/v_s)} \quad . \quad . \quad . \quad . \quad . \quad (26)$$

$$H_z = \mathscr{R} H_2 \varepsilon^{j\omega(t-z/v_s)} \quad . \quad . \quad . \quad . \quad . \quad (27)$$

and
$$J_y = \mathscr{R} J \varepsilon^{j\omega(t-z/v_s)} \quad . \quad . \quad . \quad . \quad . \quad (28)$$

where H_1, H_2 and J are functions of x. Under these conditions Maxwell's first and second equations,

$$\text{curl } H = \frac{4\pi}{10} J, \quad \text{and} \quad 10^8 \rho \text{ curl } J = -\frac{d\Phi}{dt}$$

may be written as

$$\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} = \frac{4\pi}{10} J_y \quad . \quad . \quad . \quad . \quad . \quad (29)$$

$$-10^8 \rho \frac{\partial J_y}{\partial z} = -\frac{\partial H_x}{\partial t} - v\frac{\partial H_x}{\partial z} \quad . \quad . \quad . \quad (30)$$

$$10^8 \rho \frac{\partial J_y}{\partial x} = -\frac{\partial H_z}{\partial t} - v\frac{\partial H_z}{\partial z} \quad . \quad . \quad . \quad . \quad (31)$$

Substituting eqns. (26)–(31) and solving for H_1 and H_2, we obtain

$$\left.\begin{aligned} \frac{\partial^2 H_1}{\partial x^2} &= \gamma^2 H_1 \\ \frac{\partial^2 H_2}{\partial x^2} &= \gamma^2 H_2 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

and
$$\left.\begin{aligned} \frac{\partial H_1}{\partial x} &= \frac{j2\pi}{\lambda} H_2 \\ J &= -\frac{s v_s}{10^8 \rho} H_1 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

where $\gamma = \frac{2\pi}{\lambda}(1 + jh)^{1/2}$ and where $h = 2v_s s\lambda/10^9\rho$.

The boundary equations which must be satisfied are $H_2 = 0$ and, from eqn. (33),

$$\frac{dH_1}{dx} = 0 \text{ at } x = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

This assumes in the arrangement of Fig. 7 that the core is of infinite permeability and cannot sustain the field H_2 parallel to its surface. For the second boundary condition many forms are possible. If the winding current is known,

$$H_2 = H_{2a} \text{ and } \frac{dH_1}{dx} = \frac{j2\pi}{\lambda} H_{2a} \text{ at } x = a \quad . \quad . \quad (35)$$

where $H_{2a} = (4\pi/10)dNI_T/dz$ is a reasonable approximation in most cases. If the supply voltage is known, or more accurately the induced voltage, V_i, which is the supply voltage less the voltage drop in the winding impedance,

$$H_1 = H_a \text{ at } x = a \text{ where } \frac{V_i}{N} = \frac{jv_s b H_a}{10^8} \quad . \quad . \quad (36)$$

A further possibility is to assume that the mean field across the gap is known:

$$\frac{1}{a}\int_0^a H_1 dx = H_p \quad . \quad . \quad . \quad . \quad . \quad . \quad (37)$$

using the same symbol H_p as before but denoting now the peak value in time of the mean gap field. Any of the eqns. (35)–(37) can be employed in solving eqns. (32) and (33); all have relative merits, but eqn. (37) appears to be the most convenient when comparisons with previous expressions are to be made. This boundary condition will be employed, therefore, together with that of eqn. (34), when the solution of eqn. (32) reduces to

$$\frac{H_1}{H_p} = \frac{\gamma a \cosh \gamma x}{\sinh \gamma a} \quad . \quad . \quad . \quad . \quad . \quad (38)$$

It is useful for design purposes to evaluate

$$\frac{H_a}{H_p} = \frac{\gamma a}{\tanh \gamma a} = \left|\frac{H_a}{H_p}\right| \varepsilon^{j\sigma} \quad . \quad . \quad . \quad . \quad (39)$$

This reduces to

$$\left|\frac{H_a}{H_p}\right| = (\cosh M + \cos N)\left(\frac{M^2 + N^2}{\sinh^2 M + \sin^2 N}\right)^{1/2} \quad . \quad (40)$$

and
$$\sigma = \text{arc tan}\left(\frac{N}{M}\right) - \text{arc tan}\left(\frac{\sin N}{\sinh M}\right) \quad . \quad . \quad . \quad (41)$$

where

$$M = \frac{4\pi a}{\lambda}\left[\frac{(1+h^2)^{1/2}+1}{2}\right]^{1/2} \text{ and } N = \frac{4\pi a}{\lambda}\left[\frac{(1+h^2)^{1/2}-1}{2}\right]^{1/2} \quad . \quad . \quad . \quad . \quad (42)$$

Eqns. (40) and (41) are plotted in Figs. 9(A) and 9(B) to a base of a/λ for various values of h.

It is also desirable to know the pressure difference on either side of the channel: substituting eqns. (33) and (38) in eqn. (2) and integrating this reduces to

$$\frac{p_a}{p_0} = \frac{\cosh M + \cos N}{2} \quad . \quad . \quad . \quad . \quad . \quad (43)$$

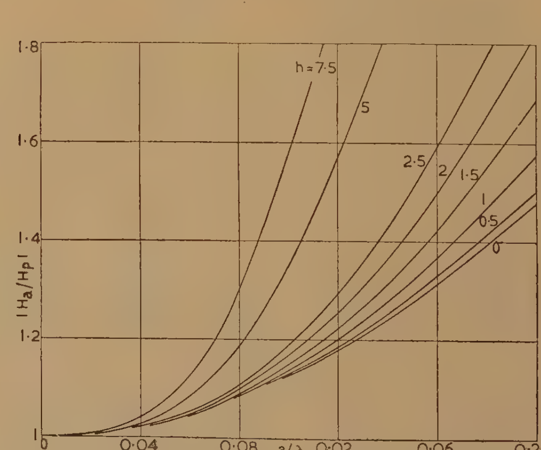


Fig. 9A.—Ratio of the field at a position near the windings to the mean field across the gap.

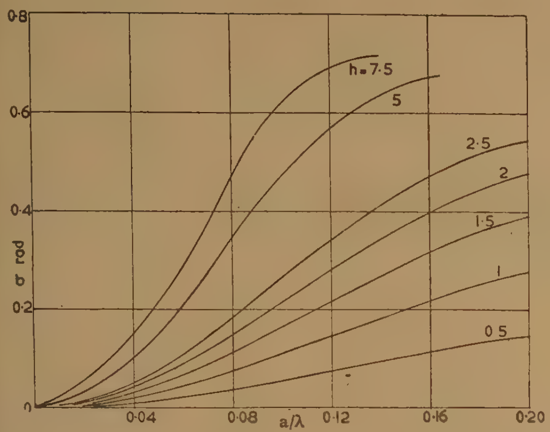


Fig. 9B.—The phase displacement σ by which H_p lags behind H_a.

The gross output power P_0', based on a pressure averaged across the gap and in time, is

$$P_0' = P_\lambda(1 - s)s\chi \quad . \quad . \quad . \quad . \quad . \quad (44)$$

and the ohmic loss in the fluid is

$$P_f = P_\lambda s^2 \chi \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

where $P_\lambda = v_s^2 ab\lambda H_p^2/(2 \times 10^{16}\rho)$ as before; the factor χ is given by

$$\chi = \frac{(M^2 + N^2)\left(\dfrac{\sinh M}{M} + \dfrac{\sin N}{N}\right)}{4(\cosh M - \cos N)} \quad . \quad . \quad . \quad (46)$$

The expressions (43) and (46) are plotted in Figs. 9(C) and 9(D) respectively, also as functions of a/λ and h. It will be noticed that χ is greater than unity, which may appear surprising at first

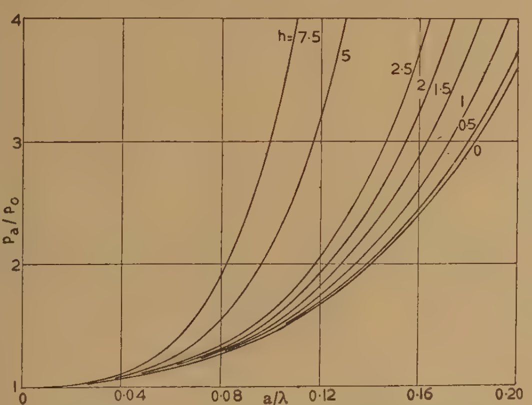


Fig. 9C.—The ratio of pressure on one side of the channel to that on the other.

sight: however, this increase is at the expense of increased input power, field H_a, tooth flux and induced voltage V_i.

In general the results of this analysis indicate that, if flux penetration effects are to be made small, then a/λ should be less than 0·1; the value of h is not subject to much control but is usually less than unity. Larger values of a/λ are permissible in practice both in the annular pump, owing to the compensating effect of the increase of field H_1 as the radius decreases, and in the flat linear induction pump when the winding is on both sides of the magnetic gap.

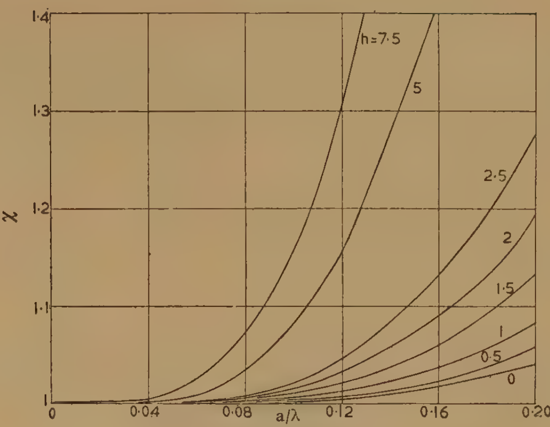


Fig. 9D.—The function χ.

(2.6) Description of Experimental Alip

An annular linear induction pump was constructed, as in Fig. 4, for sodium–potassium (eutectic) alloy to give an output of 400–500 gal/min at a pressure of 14 lb/in² falling to 10 lb/in² at the higher flow. Design details of the pump and its estimated performance at maximum efficiency are given below; experimental results, which closely confirm the design figures, are

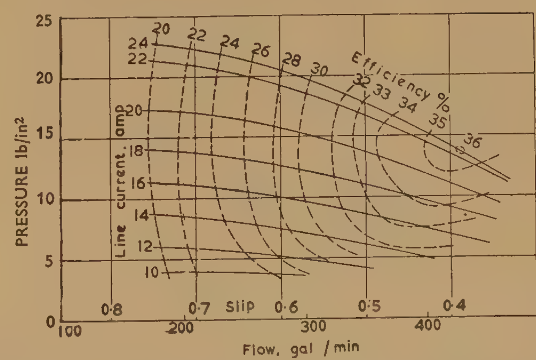


Fig. 10.—Test results of annular linear induction pump.

(Pump inlet pressure, 7 lb/in². Metal, 22/78 NaK at 175° C. Winding temperature, 100° C at maximum power.)

shown in Fig. 10. With sodium the maximum efficiency of the pump would be 41%.

Flow, q = 420 gal/min
Pressure, p = 14 lb/in²
Grading of winding, Method A
Channel width, a = 1·69 cm
Channel circumference, b = 24·6 cm
Wavelength, λ = 25·7 cm
Total number of poles, 8
Magnetic gap width, d = 2·07 cm
Tube wall thickness:
  Inner, w_i = 0·020 in
  Outer, w_0 = 0·020 in
Synchronous velocity, v_s = 1 284 cm/sec
Slip, s = 0·40
Slots per pole, 6
Coil height, 3·0 in
Coil width, 0·59 in
Maximum field in gap, H_p = 1 770 gauss

Liquid temperature, 175° C
Liquid resistivity, 45·5 μΩ cm
Liquid viscosity, 0·0035 poise
Liquid density, 0·838
Pipe wall resistivity, 112 μΩ cm

Output power	$(P_0' - P_h)$ =	3·07 kW
Hydraulic loss	P_h =	0·73
Ohmic loss in liquid	P_f =	2·77
Tube wall loss	P_t =	0·40
Winding loss	P_w =	1·33
Miscellaneous losses	P_i, etc. =	0·30
Total input power		8·60 kW
Overall efficiency		35·7%
Power factor		0·24

(2.7) Induction Pump Design Considerations

Several attempts at the design of an induction pump are usually necessary to achieve the desired balance between size, efficiency, power factor, fluid hold-up, distribution of losses, ruggedness, reliability, ease of construction and cost. In general, the highest value of fluid velocity is employed, since this gives minimum pump size and hold-up and maximum power factor; the velocity should be increased to the value where hydraulic loss, P_h, begins to reduce the efficiency. The value of slip, s, employed depends on pump size and is usually selected to give optimum efficiency conditions over the operating range of flow and pressure. A large channel width, a, reduces pump size and tube wall loss, P_t, thus permitting the use of a thicker pump channel, but it also reduces the power factor and increases the winding loss P_w. More complete details of the effects of change of design parameters are summarized in Table 1, which applies particularly near optimum efficiency conditions.

Table 1

THE EFFECTS ON PUMP DESIGN OF CHANGE OF FLUID VELOCITY v, SLIP s, CHANNEL WIDTH a, HEAT INSULATION w_i, AND NUMBER OF POLES

Quantity increased in value	Resulting change in pump design features							
	P_f	P_t	P_h	P_w	H	H_L*	P.F.	Heat leak†
Fluid velocity, v ..	i	i	I	R	R	R	I	—
Slip, s	I	—	i	r	R	R	I	—
Channel width, a ..	—	R	R	I	—	I	R	R
Insulation thickness, w_i	—	—	—	I	—	I	R	R
Number of poles ..	—	—	I	R	R	R	I	I

* Leakage field.
† Heat transferred to or from liquid metal.
I increased; i increased slightly;
R reduced; r reduced slightly.

(2.8) The Spiral Induction Pump

The spiral induction pump has many design features in common with both the induction motor and the linear induction pump, and under ideal conditions with end-rings of zero resistance and many turns of the spiral the design equations of the linear pump mid-section apply. However, in general the axial component of the motion of the liquid cannot be ignored, and the effect this has on pump performance will now be examined briefly.

The field and flux in the spiral induction pump take their ideal forms

$$H = H_p \sin(\omega t - 2\pi z/\lambda) \quad \text{and} \quad \Phi = \Phi_0 \cos(\omega t - 2\pi z/\lambda)$$

where $\Phi = \lambda b H_p/2\pi$. Since the liquid velocity vector is inclined at an angle δ to the synchronous velocity vector, as indicated in Fig. 11, the difference velocity $(v_s - v)$ has a component in phase,

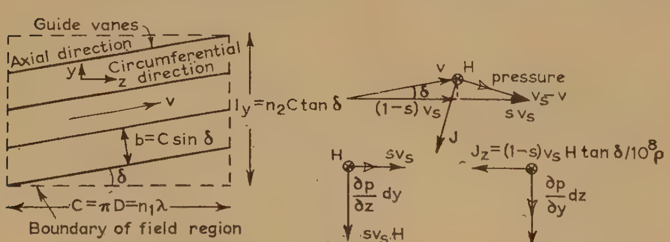


Fig. 11.—Effect of axial motion of liquid on performance of spiral induction pump.

sv_s, and one in quadrature, $v \sin\delta = (1 - s)v_s \tan\delta$, with the circumferential direction z. These two components induce two components of electric field: $E_y = sv_sH_p10^{-8}$ and $E_z = -(1 - s)v_s \tan\delta H_p10^{-8}$. The resultant current-density distribution is very complicated and is made further involved if the finite resistance of the end-rings is brought into consideration. With low-resistance end-rings it is reasonably accurate to assume that E_y is dissipated in ohmic drop as it is induced, giving $J_y = E_y/\rho = sv_sH_p/10^8\rho$. It is less accurate to write $J_z = E_z/\rho$, since the current-density pattern in this case is a complicated two-dimensional function; however, in the limiting case when l_y/λ is small, this is reasonably true when

$$J_z = -(1 - s)v_sH_p \tan\delta/10^8\rho$$

Thus the average value of pressure developed is given by

$$\frac{dp}{dz} = \frac{J_yH_p}{20} = \frac{sv_sH_p^2}{2\times 10^9\rho} \quad \text{and} \quad \frac{dp}{dy} = \frac{J_zH_p}{20} = \frac{-(1-s)v_sH_p^2\tan\delta}{2\times 10^9\rho} \quad . \quad . \quad . \quad . \quad (47)$$

Since

$$\frac{dp}{ds} = \frac{dp}{dz}\frac{dz}{ds} + \frac{dp}{dy}\frac{dy}{ds} = \frac{sv_sH_p^2}{2\times 10^9\rho}\left[\cos\delta - \frac{1-s}{s}\tan\delta\sin\delta\right]$$

then on integrating

$$p = \frac{dp}{ds}\frac{n_2C}{\cos\delta} = \frac{sv_sH_p^2n_2C}{2\times 10^9\rho}\left[1 - \frac{1-s}{s}\tan^2\delta\right] \quad . \quad (48)$$

and

$$P'_0 = pvab10^{-7} = k_0P_\lambda s(1-s) \quad . \quad . \quad . \quad (49)$$

where $k_0 = \frac{n_1n_2}{\cos\delta}\left[1 - \frac{1-s}{s}\tan^2\delta\right]$, $P_\lambda = \frac{v_s^2H_p^2ab\lambda}{2\times 10^{16}\rho}$

as before, and n_1 and n_2 are the number of pole pairs and spirals respectively. The ohmic loss in the liquid is

$$P_f = \rho J^2\,(\text{vol.}) = k_fP_\lambda s^2, \text{ where } k_f = \frac{n_1n_2}{\cos\delta}\left[1 + \left(\frac{1-s}{s}\right)^2\tan^2\delta\right] \quad . \quad . \quad . \quad . \quad (50)$$

Making substitutions as before, the tube-wall loss is

$$P_t = k_{t1}k_{t2}P_\lambda, \text{ where } k_{t2} = \frac{n_1n_2}{\cos\delta} \quad . \quad . \quad . \quad (51)$$

It is evident from eqns. (49) and (50) that the power output falls and the ohmic loss in the fluid rises above their ideal values when the slip is small and the angle of the spiral δ is large. However, the additional terms are usually small in those cases for which the spiral pump is normally to be preferred over the linear induction pump, i.e. when the flow is low and the pressure high and the channel long and narrow.

(3) THE CONDUCTION PUMP—D.C. AND A.C.

(3.1) The Ideal D.C. Conduction Pump

In the simplest and ideal form of d.c. conduction pump, the liquid-metal current density is uniform within the region of the gap and zero outside, and the field also is uniform. Under these conditions, eqns. (1)–(4) can be applied directly, when the pump pressure becomes

$$p = \frac{JHc}{10} = \frac{HI}{10a} = \frac{4\pi(NI)_mI}{100ad} = \frac{\Phi I}{10abc} \quad . \quad . \quad (52)$$

and the output power is

$$P'_0 = abcJHv10^{-8} = (Jac)(Hvb10^{-8}) = IV_i \quad . \quad (53)$$

where V_i is the induced voltage due to the motion of the liquid in the magnetic field and I is the total electrode current. The ohmic loss in the liquid metal is

$$P_f = \rho J^2 abc = \rho I^2 b/ac = RI^2 \quad . \quad . \quad . \quad (54)$$

It is interesting to consider for this idealized case the factors which control the pump geometry. To achieve a high pressure and yet be economical in magnetizing ampere-turns, NI_m, and electrode current, I, it is evident from eqn. (52) that a and d should be small, but a and d cannot be reduced indefinitely owing to limitations imposed by tube-wall thickness and hydraulic loss. For economy in magnet power the flux should also be limited, and this demands that b and c also should be small, and about the same order of magnitude if fringing flux is to be kept small. A low value of P_f demands a small value of b and large values of a and c. Hydraulic and field power requirements have already controlled the values of a and b fairly closely, so it is only possible to influence c, which should be large in comparison with b, but not too large in order to limit leakage flux and hydraulic losses. Thus the general conclusions would follow that c should be several times greater than b, and b several times greater than a, which should always be as small as possible. In practice the situation is more complicated than this. Table 2 gives more complete details of the change in pump performance with variation of its design parameters.

The field of the d.c. pump can be provided by an electromagnet or a permanent magnet. An electromagnet can be separately excited or excited from the electrode current supply, or both methods can be combined. However, shunt, series or compounded windings do not produce markedly different characteristics as with d.c. rotary machines, since the induced e.m.f. term, V_i, is comparable with or even smaller than the ohmic drop in busbars, liquid metal and generator resistance. If the electrode current source also provides the field, the natural arrangement is to employ a series winding to avoid increasing the already undesirably high current and to increase the voltage, which is inconveniently low.

Whatever the arrangement, the ratio to be adopted of H (or NI_m or Φ) to I is of importance, and in general that ratio will be chosen which gives best efficiency, smallest excitation current, smallest size, or satisfies other considerations of a general nature. However, there are limits to the ratio H/I which can be adopted. If H is gradually increased with I kept constant, the pump performance shows an optimum. This is due to the effect of tube-wall currents I_t (see Fig. 17) and of a current I_0, with components I_{0i} and I_{0o} at inlet and outlet respectively, which flow outside the pole region where only the ohmic drop restricts current flow and not, as within the pole, the induced voltage term V_i as well: as H increases, I_0 and I_t increase relative to I, and the performance falls off. On the other hand, if H is kept constant and the electrode current is gradually increased, there is another performance optimum. This is due to 'armature-reaction' effects, where the current in the liquid and tube walls modify the field in the gap. These effects will be considered in turn.

(3.2) The Effects of Wall and End Currents

Following Barnes,[5] it is convenient to denote by R_t the resistance between the electrodes of the tube wall, and by R_0 the resistance of the liquid metal outside the pole region, wherein flows the current I_0. The parallel resistance of R_0 and R_t can be denoted by R_p. If R is the resistance of the liquid metal within the pole region itself, then the equivalent circuit is as shown in Fig. 12. From Kirchhoff's laws it follows that $I_s R_p = I(R_p + R) + V_i$, so, substituting for I in eqn. (52), the pressure becomes

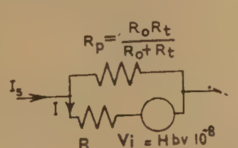


Fig. 12.—Equivalent inter-electrode circuit of d.c. conduction pump.

$$p = \frac{H}{10a}\,\frac{I_s R_p - Hq/a10^8}{R_p + R} \quad . \quad . \quad . \quad . \quad (55)$$

Both pressure and flow show a maximum as H is increased. If q is constant,

$$p_{max} = H^2 q/a^2(R_p + R)10^9 \text{ at } H = I_s R_p a 10^8/2q \quad . \quad (56)$$

If the field H is excited by N turns of current I_s, then $H = 4\pi N I_s/10d$ and the optimum number of turns for maximum pressure conditions is $N_0 = R_p a d 10^9/8\pi q$.

In d.c. conduction pump design the estimation of R_t is simple and Fig. 13, which is self-explanatory, should assist the calculation. It is more difficult to estimate R_0, however, and, though Fig. 13 should help, as Barnes points out, R_0 'is a complicated function of tube and magnet geometry, field distribution and liquid velocity profile'; he recommends its determination by experimental test.

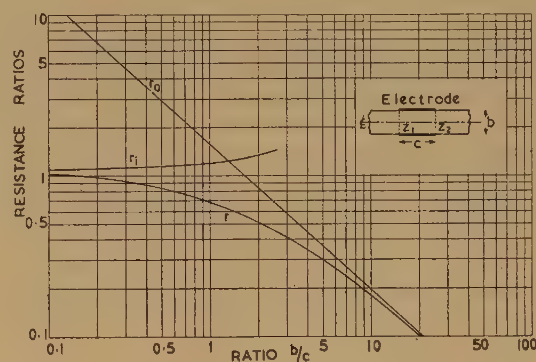


Fig. 13.—Fringing resistance curve.

$$r = Vc/\rho b \int_{-\infty}^{+\infty} Jdz, \quad r_0 = Vc/\rho b\left(\int_{-\infty}^{z_1} Jdz + \int_{z_2}^{\infty} Jdz\right)$$

and $r_i = Vc/\rho b \int_{z_1}^{z_2} Jdz$, where V is voltage across electrodes, J the current density at centre line and ρ the resistivity of conducting strip.

The end-currents can be limited in two ways: by insulating the tube walls and inserting insulating baffles in the tube outside the field and electrode region, and by grading the field at inlet and outlet, gradually increasing the field to a maximum within the electrode region, while keeping the increase in field in step with the increase in current density. Baffles can be used sometimes, but they are often difficult to install and they will not be considered further.

In estimating the optimum field grading, the fringing curves of Fig. 14 should be useful. Fig. 14(*a*) shows the fringing of field near a pole,[6] and Fig. 14(*b*) the fringing of current density between electrodes, both for two-dimensional fields. Since the value of b is usually larger than a, the inherent fringing of the field is generally insufficient to match the fringing of the current density, and it must be increased either by tapering the gap at entry and outlet or, which is sometimes preferable, by distributing the magnetizing turns in slots in the graded regions. The effect of gradually increasing the field will be to spread the current density further, so the length of the graded field region should be slightly longer than Fig. 14(*b*) shows to be desirable. It

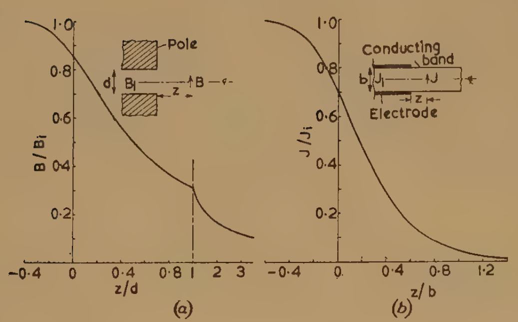


Fig. 14.—Fringing curves (*a*) for flux density between poles and (*b*) for current density between electrodes.

should not be too gradual, however, or the tube-wall loss will be increased. In practice, the optimum length of graded region is not critical, and it should be possible to determine by common-sense modifications to Fig. 14 the desired field distribution at entry and outlet.

The end-current effects are more troublesome as the ratio of the induced e.m.f. to the ohmic drop $Hv/\rho J$ increases; thus field grading is more necessary with fluids like sodium than bismuth, for sodium has a low resistivity and permits a higher velocity to be employed, owing to its lower viscosity and density. Accurate field grading is also more desirable with large pumps.

(3.3) Armature Reaction Effects in the Ideal D.C. Conduction Pump

In a conduction pump, the current in the liquid metal produces a field linking it, as indicated by the broken line of Fig. 15A, of direction such as to strengthen the main field at inlet and

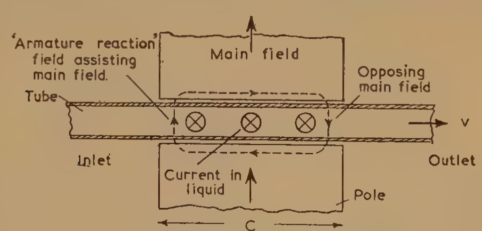


Fig. 15A.—'Armature-reaction' effects in the d.c. pump.

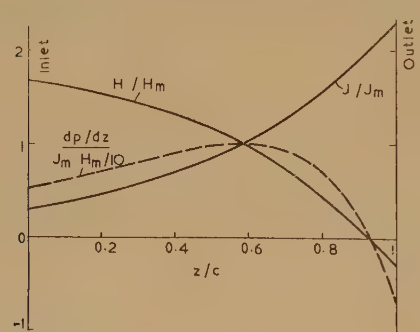


Fig. 15B.—Pressure, field and current density distribution along a d.c. conduction pump showing 'armature-reaction' effects.

weaken it at outlet. This change in the field distribution produces a further change in the current density distribution J in the liquid metal. If the voltage across the electrodes is V, then the current density is given by $\rho Jb = V - V_i = V - Hbv/10^8$, assuming uniformity in the x- and y-directions; so a decrease in the field causes an increase in the current density, and vice versa. Fig. 15B shows the variation of H, J and dp/dz along the length of the pump, arising from armature reaction. It will be seen that dp/dz is everywhere less than its ideal value of $J_m H_m/10$ as given by eqn. (1), where J_m and H_m represent mean values integrating in the z-direction; thus, armature reaction causes a reduction in the mean pump pressure.

These effects will now be examined in more detail, assuming the somewhat idealized conditions that no current flows outside the pole and electrode region and assuming only the components J_y, H_x and v_z to be present, as in Fig. 5, and neglecting their variation with both x and y. Then Maxwell's first and second equations can be expressed as

$$-\frac{dH}{dz} = \frac{4\pi J}{10} \quad . \quad . \quad . \quad . \quad . \quad . \quad (57)$$

and

$$V = \rho Jb + Hvb/10^8 \quad . \quad . \quad . \quad . \quad (58)$$

Differentiating eqn. (58) with respect to z and substituting from eqn. (57), then

$$\frac{d^2H}{dz^2} = \frac{4\pi v}{10^9\rho}\frac{dH}{dz} \quad . \quad . \quad . \quad . \quad . \quad . \quad (59)$$

for which the solution is

$$H = A + B\varepsilon^{2\beta z/c} \quad . \quad . \quad . \quad . \quad . \quad . \quad (60)$$

where $\beta = 2\pi vc/10^9\rho$. If the boundary conditions are expressed in the form

$$H_m = \frac{1}{c}\int_0^c Hdz \text{ and } J_m = \frac{1}{c}\int_0^c Jdz = \frac{10}{4\pi c}(H_0 - H_c)$$

the solution becomes

$$H = H_m + \frac{H_i}{\beta}\left(1 - \frac{2\beta\varepsilon^{2\beta z/c}}{\varepsilon^{2\beta} - 1}\right) \quad . \quad . \quad . \quad (61)$$

where H_i is a convenient parameter of physical significance, indicating the maximum field at the pole edges at $z = 0$ and $z = c$ which would be produced by the current in the liquid metal; it is given by

$$H_i = \frac{2\pi J_m c}{10} = \frac{4\pi I}{10 \times 2a} = \frac{H_0 - H_c}{2} \quad . \quad . \quad (62)$$

Substituting eqn. (61) in eqn. (57) yields the expression for the current density:

$$J = J_m\frac{2\beta\varepsilon^{2\beta z/c}}{\varepsilon^{2\beta} - 1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (63)$$

Eqns. (62) and (63) are shown plotted for a particular case in Fig. 15(*b*). Substituting these expressions in eqns. (2)–(4) gives

$$p = \frac{H_m J_m c}{10}\left(1 - \frac{H_i}{H_m}\,\frac{\beta\coth\beta - 1}{\beta}\right) \quad . \quad . \quad (64)$$

$$P_0' = \frac{H_m J_m abcv}{10^8}\left(1 - \frac{H_i}{H_m}\,\frac{\beta\coth\beta - 1}{\beta}\right) \quad . \quad . \quad (65)$$

$$P_f = \rho J_m^2 abc\beta\coth\beta \quad . \quad . \quad . \quad . \quad . \quad (66)$$

and

$$\eta_i = \frac{P_0'}{P_0' + P_f} = 1 - \frac{\beta\coth\beta}{1 + \beta H_m/H_i} \quad . \quad . \quad (67)$$

For convenience the expressions $\beta\coth\beta$ and $(\beta\coth\beta - 1)/\beta$ are given in Fig. 16. Expressions somewhat similar to eqns. (64)–(67) are derived by Woodrow.[7]

It is interesting to consider the effect of increasing the current or current density keeping H_m, v and the pump dimensions constant. Under these conditions the power output can be written in the form $P_0 = k_1 H_i(1 - k_2 H_i)$, where k_1 and k_2 are constants, which has a maximum at $H_i = 1/(2k_2)$. Thus the

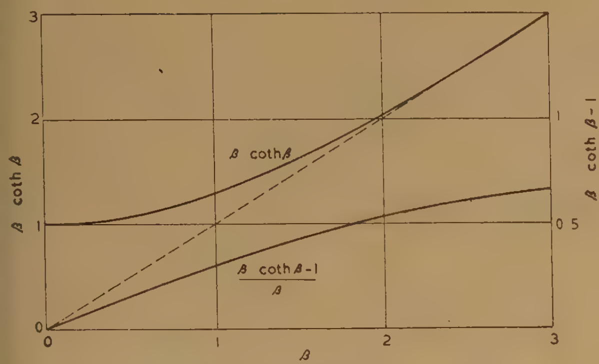


Fig. 16.—The functions $\beta \coth \beta$ and $(\beta \coth \beta - 1)/\beta$.

pressure and power output is a maximum when the current is increased to the value at which

$$\frac{H_i}{H_m} = \frac{\beta}{2(\beta \coth \beta - 1)} \quad . \quad . \quad . \quad . \quad (68)$$

when the maximum power output is

$$P_0' = \frac{H_m J_m abcv}{2 \times 10^8} \quad . \quad . \quad . \quad . \quad . \quad . \quad (69)$$

and the ideal efficiency is

$$\eta_i = \frac{P_0'}{P_0' + P_f} = \frac{\beta \coth \beta - 1}{2\beta \coth \beta - 1} \quad . \quad . \quad . \quad (70)$$

This expression has a maximum value of 50% at large values of β.

To summarize: it is shown that for a given mean field H_m and fluid velocity v, the electrode current I can be increased, with corresponding increase of the output power only up to a certain point; beyond that point the power falls off. At the maximum position, the power output is only half of what it would be if the pump were perfectly compensated for 'armature reaction', the ohmic losses are higher and the efficiency lower, at best being only 50%. These effects are due to the modification of the field by the current in the liquid and the consequent redistribution of the current density in the liquid. The controlling factors are H_i/H_m and β or, in alternative form, $H_i/\beta H_m = RI/V_i$ and β. The factor β is proportional to vc/ρ, and so armature reaction effects are more pronounced in large pumps than small and with liquids like sodium rather than bismuth, just as end effects are more serious under these conditions.

(3.4) The Compensated and Over-Compensated D.C. Pump

If the conductor to an electrode is taken through the pole as a flat strip or pole-face winding, the armature reaction effects can in principle be eliminated, and the pump equations return to their ideal form as in eqns. (52). Ideal compensation is not realizable in practice owing to the current at the ends I_0 and wall current I_t. To achieve the best possible armature reaction compensation, the return conductor should be so distributed that the current in it is as near as possible to the parent current in the liquid and the wall, and equal in magnitude; to do this may mean arranging for the compensating winding to extend into the graded regions or beyond the poles. As this is not always convenient it is worth while to consider the effect of over-compensation, where the return current is wholly within the pole and is greater by a factor k than the current in the liquid metal within the pole. To help clarify the picture and to give a guide to the extent to which the following analysis fits practice, Fig. 17 should be useful. In this Figure the various currents which are

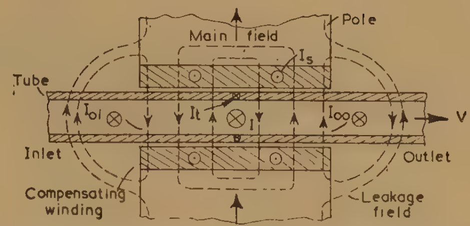


Fig. 17.—Diagram illustrating the component currents in a d.c. conduction pump and their associated fields.

involved are shown by circles at relevant and typical positions, and the fields associated with their currents are also indicated. It will be seen that, provided the end currents at inlet and outlet are equal, i.e. $I_{0i} = I_{0o}$, their fields will cancel and the conditions inside the gap can be analysed by assuming only I_s and I to be present. However, since the compensating winding current I_s exceeds that in the liquid I by I_0 (or $I_{0i} + I_{0o}$), the field will be strengthened at the outlet and weakened at the inlet; hence I_{0i} will be larger than I_{0o}, thus weakening the main field.

To simplify calculation an analysis will now be made of the compensated pump in which currents I_s and I only are assumed present. (It is possible to extend the analysis further to predict I_{0i} and I_{0o}, and estimate the reduction in field H due to I_{0i} exceeding I_{0o}.) For the over-compensated pump assume $I_s = kI$, where k is greater than unity. If a uniform distribution of I_s over both pole faces is assumed, then eqn. (57) takes the form

$$-\frac{dH}{dz} = \frac{4\pi}{10}(J - kJ_m) \quad . \quad . \quad . \quad . \quad (71)$$

where $J_m = 1/c\int_0^c Jdz$, while eqn. (58) remains unchanged. It follows from an argument as in the uncompensated case that the field is

$$H = H_m - \frac{k-1}{\beta}H_i\left(1 - \frac{2\beta\varepsilon^{\frac{2\beta}{c}z}}{\varepsilon^{2\beta} - 1}\right) \quad . \quad . \quad . \quad (72)$$

where H_i, H_m and β have the same meaning as before; the current density is

$$J = J_m\left[k - \frac{2\beta(k-1)\varepsilon^{\frac{2\beta}{c}z}}{\varepsilon^{2\beta} - 1}\right] \quad . \quad . \quad . \quad . \quad (73)$$

The pump pressure is

$$p = \frac{H_m J_m c}{10}\left[1 - (k-1)^2\frac{H_i}{H_m}\frac{\beta \coth \beta - 1}{\beta}\right] \quad . \quad (74)$$

and the output power is

$$P_0' = pq/10^7, \text{ as before} \quad . \quad . \quad . \quad . \quad (75)$$

The ohmic loss in the liquid metal is

$$P_f = pabcJ_m^2[1 + (k-1)^2(\beta \coth \beta - 1)] \quad . \quad (76)$$

If $k = 2$, that is the pump is as much over-compensated as it was previously under-compensated, then eqns. (64) and (74) and eqns. (66) and (76) are identical. Thus, if the compensating winding is within the pole it may still not eliminate undesirable armature reaction effects if the end current I_0 is appreciable.

(3.5) General Design Considerations

Table 2 shows the relative features of different designs of pump for a specified output pressure and flow. It is assumed that compensation is provided for armature reaction by a com-

Table 2

THE EFFECTS ON D.C. CONDUCTION PUMP PERFORMANCE OF CHANGES IN FLUID VELOCITY, MAGNETIZING TURNS, CHANNEL BREADTH TO THICKNESS RATIO, AND CHANNEL LENGTH

Quantity *increased* in value	Resulting changes in pump design features						
	Efficiency η	Pump weight	Supply current I_s	Ratio I/I_s	Optimum magnetizing turns N_0	Field power	Field H
Fluid velocity, v	—	R	r	R	R	r	i
Magnetizing turns, N	—	I	R	R	—	I	I
Ratio, b/a (with product ab constant)	r	I	R	R	r	R	i
Pump length, c	I	I	—	i	r	i	r

I increased; i increased slightly;
R reduced; r reduced slightly.

pensating winding and for end effects by flux fringing. The Table applies particularly to pumps rated at 500 g.p.m. or more, and up to 100 lb/in^2; it is not necessarily accurate in all circumstances.

The most severe conflict in pump design is between efficiency, pump size and supply current: an improvement in one usually means the others worsen. In practice, the most economical arrangement is best determined by costing a number of different designs; in a reactor pump this is quite involved and necessitates close co-operation between reactor and pump designer.

Owing to end effects it is difficult to design a d.c. pump with the precision of a linear induction pump, but nevertheless it should be possible to estimate the efficiency to within $\pm 5\%$ or better; however, tests on a model should help to determine parameters in doubt, and this would appear to be advisable before constructing a large pump.

(3.6) The A.C. Conduction Pump

The performance of the a.c. conduction pump is more difficult to calculate rigorously than that of the d.c. pump, and even the solution of the ideal a.c. pump, examined by Murgatroyd,[8] is very complicated. However, most practical forms of a.c. pump can be designed using the expressions derived for the d.c. pump, and the effects of eddy losses in the liquid metal, tube walls and compensating windings can be calculated separately. This is so because, in practice, excessive eddy-current loss cannot be allowed, so the solution of the eddy-current problem in its most general and difficult form is mainly of academic interest; it is more important to know the point at which eddy currents are just tolerable in magnitude and do not produce serious field distortion and excessive losses. Fortunately the eddy current and the useful conduction current in the liquid metal are in quadrature and therefore do not interact with each other unduly; this permits independent evaluation and superposition of the effects even when the eddy currents are quite large.

The eddy currents which exist in the a.c. conduction pump are as follows: (*a*) eddy currents in the tube walls; (*b*) eddy currents in the liquid metal which are similar, if the complication due to movement of the liquid is ignored; (*c*) induced current in the compensating winding which can be most serious unless several parallel windings and separate electrodes are employed with the induced current in them forced to flow through the tube wall and liquid metal.

It is evident that an a.c. induction pump cannot be operated with the channel width b and a pole width c so large that eddy currents in the liquid metal seriously inhibit flux penetration. A reasonable restriction to impose on the design, therefore, is to say that the channel width b or pole width c must be less than $2d_p$, where d_p is the depth of penetration given by the well-known formula $d_p = (10^9\rho/8\pi^2 f)^{1/2} = 3\cdot55(10^6\rho/f)^{1/2}$ cm. The permeability of the liquid is assumed unity. As an example, for sodium at 200° C and 50 c/s, d_p is 1·8 cm, so a.c. conduction pumps with a channel greater than 3·6 cm wide will suffer serious flux distortion; for liquid bismuth at 400° C, d_p is 5·5 cm, and a channel of up to about 10 cm wide is feasible.

The electrode current itself can be derived from a separate transformer with its voltage supply at a suitable phase displacement with respect to the voltage supply to the field coils, or a three-limbed iron circuit can be employed in which transformer action induces the electrode current which also provides the field m.m.f.[11]

(4) CONCLUSIONS—COMPARISON OF PUMP TYPES

Electromagnetic pumps are usually of appreciably lower efficiency—and power factor for a.c. types—than electrical rotating machines of corresponding rating, owing mainly to the high resistivity of the liquid metal compared with copper and to the sharply conflicting hydraulic and electrical requirements. Moreover, the efficiency is often reduced further by losses which have no parallel in rotating machines. In conduction pumps, for example, a large loss can be produced by the component of electrode current which flows in the tube wall and in the liquid outside the pole and field region, where, since the induced voltage due to fluid motion in the field is absent, ohmic resistance alone limits current flow. 'Armature reaction' can also produce serious effects which can limit output and efficiency. In the linear induction pump, starting and stopping the travelling wave of field and flux introduces pulsating components of flux, which can give rise to large additional losses. In the spiral induction pump the axial component of fluid motion produces a circumferential current and an associated power loss.

The different types of conduction and induction pump compete with and are complementary to each other. The a.c. conduction pump is restricted to small power applications, since eddy-current losses increase rapidly with size. It suffers from a poor power factor, and it is usually appreciably larger than a d.c. pump of similar output, but it avoids d.c. supply difficulties where thousands of amperes are required at a one-volt level. In general, the a.c. conduction pump is convenient in small liquid-metal-circuit work, where it is versatile and accommodates a wide range of liquids, but it gives way to d.c. pumps with bismuth at higher power levels and to induction pumps with sodium at all but the lowest power level.

The d.c. conduction pump has the best performance figures of any pump with bismuth at all power levels. With sodium it is as good as any in efficiency, but when considered in con-

Table 3

PERFORMANCE DATA OF CONDUCTION AND INDUCTION PUMPS

Conduction Pumps

Type	Fluid	Flow	Pressure	Output	Efficiency	P.F.	Supply: Voltage	Supply: Current	Power		Authority (Ref. No.)
		g.p.m.	lb/in²	h.p.	%		volts	kA	h.p./ton	h.p./ft³	
A.C. ..	Mercury	6	15	0·067	~4	0·26	—	—	1·7	0·2	*
A.C. ..	NaK 400° C	20	10	0·14	—	—	—	—	1·3	0·08	(11)
Spiral D.C.	Bismuth 500° C	0·66	60	0·027	~1	—	1·2	1·4	1·9	0·4	†
D.C. ..	Bismuth 200° C	10	60	0·42	12	—	0·6	4·4	5	0·7	†
D.C. ..	NaK 250° C	300	40	8·4	44	—	0·75	19	—	—	(5)
D.C. ..	Bismuth 550° C	2000	75	105	30	—	2·6	100	40	6	†
D.C. ..	Sodium 410° C	8300	75	435	~50 ~45 overall‡	—	2·5	200	—	~2 ~0·5 total‡	(13)

Induction Pumps

Type	Fluid	Flow	Pressure	Output	Efficiency	P.F.	Supply frequency	Power		Cooling required	Authority (Ref. No.)
		g.p.m.	lb/in²	h.p.	%		c/s	h.p./ton	h.p./ft³		
Sip ..	Sodium at 400° C	25	60	1·05	22	0·56	50	4	0·3	3–4 kW	†
Sip ..	Sodium at 400° C	312	40	8·7	18·5	0·8	25	13	—	10^3 ft³/min of air	(11)
Alip ..	NaK at 175° C	420	14	4·1	36	0·22	50	11	0·9	3·5 kW	*
Alip ..	Sodium at 500° C	400	50	14	36	0·30	50			10 kW	†
Flip ..	Sodium at 370° C	1200	40	34	36	0·45	60	12	—	2000 ft³/min of air	(11)
Alip ..	Sodium at 400° C	8300	75	435	45	0·48	50	64	4·5		

* Test results by author.
† Predicted figures by author.
‡ Includes space occupied by and losses in homopolar generator and induction motor.

junction with its supply rectifier or homopolar-generator set, it is usually much less convenient than the induction pump. A particular advantage of the d.c. pump is the low-level insulation requirements. Performance data of particular conduction and induction pumps, listed in increasing values of horse-power, are summarized in Table 3.

Induction pumps handle fluids like bismuth with great difficulty: they are of no use at low power and just become practical at high power, although they still remain unattractive owing to their large size, low efficiency, poor power factor and large hold-up of fluid. With fluids of low resistivity, viscosity and density like sodium, sodium–potassium and lithium, however, it is quite different: the spiral induction pump deals effectively with low-power and high-pressure low-flow applications; the linear induction pump deals with most larger power applications. Table 3 gives some indication of the variation of performance with size. Descriptions of other pumps, both mechanical and electromagnetic, are given in References 14 and 15.

The 8300 g.p.m. Alip in the Table is designed for the same duty requirements as the 8300 g.p.m. d.c. conduction pump, intended for the EBR–II reactor.[13] The Alip replaces the d.c. pump, homopolar generator and induction motor in this arrangement, giving a similar overall efficiency with an eight- or ninefold reduction in size.

The two forms of linear induction pump also have relative merits. The flat linear induction pump (Flip) has the advantage that the windings can be placed on either side of the channel, and this improves the field uniformity and reduces the leakage reactance of the winding. The windings, too, can be easily removed without disturbing the pipework. The annular linear induction pump (Alip) has the advantage that the tube is cylindrical and therefore can be made to withstand a vacuum and a higher pressure. In addition, the current flows circumferentially in the annular space between core and winding and is at all times within the liquid metal; in the Flip, electrodes are normally brazed to the tube walls, and the current must pass from the liquid to the electrodes. These side-electrodes are necessary if a high efficiency is to be maintained, but at the same time they serve to increase the losses compared with the Alip, owing to ohmic and eddy-current losses in them. A further advantage of the Alip pump is the simplicity of the winding, which takes the form of pancake coils spaced along the tube, and the ability to grade the end-sections of the winding in a more elaborate manner than with the Flip, which can lead to better 'end-compensation' and higher efficiency. The disadvantages of being unable to remove the winding without disturbing the pipework can be overcome by arranging the winding in two sections on opposite sides of the pump, somewhat like the Flip winding; alternatively a coaxial-flow arrangement can be employed in which the liquid metal flows in a tube inside the core, reverses direction at the end of the pump and returns in the annular space between core and winding; then the windings can be withdrawn over the free end.

(5) ACKNOWLEDGMENTS

The author is indebted to his colleagues in the Research Laboratory of the British Thomson-Houston Co., Ltd., Rugby, for their assistance in constructing and testing the pumps, and to Mr. A. H. Maggs of the Motor Engineering Department for ideas in connection with end-compensation of the linear induction pump. Thanks are also due to Mr. T. I. M. Crofts of the United

Kingdom Atomic Energy Establishment, Windscale, Cumberland, for the exhaustive tests he made on the annular linear induction pump, which are summarized in Fig. 10. Much of the work recorded in the paper was performed at the request of the Atomic Energy Research Establishment, Harwell, and the author gratefully acknowledges their permission to publish the results and the encouragement and assistance received from members of the Establishment, in particular from Dr. P. Fortescue, Mr. D. A. Watt and Dr. W. Murgatroyd.

(6) REFERENCES

(1) LYON, R. N. (Ed.): 'Liquid Metals Handbook' (Office of Naval Research, U.S. Navy Department), p. 245.

(2) HARTMANN, J., and LAZARUS, F.: 'Experimental Investigations on the Flow of Mercury in a Homogeneous Magnetic Field', *Det Kgl. Danske Videnskabernes Selskab.*, 1937, **15**, p. 7.

(3) MURGATROYD, W.: 'Experiments on Magneto-Hydrodynamical Channel Flow', *Philosophical Magazine*, 1953, **44**, p. 1348.

(4) BRYANT, J. M., and JOHNSON, E. W.: 'Alternating Current Machinery' (McGraw-Hill, 1935), p. 457.

(5) BARNES, A. H.: 'Direct Current Electromagnetic Pumps', *Nucleonics*, January, 1953, p. 16.

(6) BLAKE, L. R.: 'The Design of Electromagnets', *Electronic Engineering*, Vol. XXV, Nos. 307 and 308, September and October, 1953.

(7) WOODROW, J.: 'The D.C. Electromagnetic Pump for Liquid Metals', A.E.R.E. E/R. 452, December, 1949.

(8) MURGATROYD, W.: 'Theory of the Ideal A.C. Conduction Pump', A.E.R.E. ED/R. 1566.

(9) WATT, D. A.: 'A Study in Design of Travelling Field Electromagnetic Pumps for Liquid Metals', A.E.R.E. ED/R. 1696.

(10) WOOLLEN, W. B.: 'Electromagnetic Pumps for Liquid Metals', *Fluid Handling*, April, 1955, p. 90.

(11) CAGE, J. F.: 'Electromagnetic Pumps for High Temperature Liquid Metal', *Mechanical Engineering*, June, 1953, p. 467.

(12) BRILL, E. F.: 'Development of Special Pumps for Liquid Metal', *ibid.*, May, 1953, p. 369.

(13) BARNES, A. H.: 'Pumping of Liquid Metals', *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy*, 1955, **9**, p. 259.

(14) 'Pumps for Reactor Coolants', *Nucleonics*, 1955, **13**, p. 78.

(15) 'Reactor Handbook: Engineering', U.S. Atomic Energy Commission (McGraw-Hill, 1955), p. 346.

(7) APPENDICES

(7.1) Design Equations of the Induction Pump

The following quantities are of importance in induction pump design: the core flux Φ; the gap field H; the current density in the fluid, J_f, and in the tube walls, J_t; the magnetizing current-turns per unit length, dNI_m/dz; and the induced voltage per turn, V_i/N. The relations between these quantities are given in eqns. (7)–(9). With these quantities derived and using eqns. (1)–(4) it is possible to deduce the mean pump pressure, p; the gross output power, P'_0; the ohmic loss in the fluid, P_f, and in the tube walls, P_t.

(7.1.1) Ideal Linear Induction Pump.

These equations are applicable in the mid-region of the end-compensated pump or in the spiral induction pump of small helix angle.

$$\Phi = \Phi_0 \cos(\omega t - \psi); \quad H = H_p \sin(\omega t - \psi) \quad . \quad (77)$$

$$J_f = \frac{sv_s}{10^8 \rho} H_p \sin(\omega t - \psi); \quad \frac{dNI_m}{dz} = \frac{5d}{\lambda} H_p \cos(\omega t - \psi) \quad (78)$$

$$J_t = \frac{v_s}{10^8 \rho_t} H_p \sin(\omega t - \psi); \quad \frac{V_i}{N} = \frac{v_s b}{10^8} H_p \sin(\omega t - \psi) \quad (79)$$

$$p = \frac{sv_s\lambda}{2 \times 10^9 \rho} H_p^2; \quad P'_0 = \frac{pq}{10^7} = P_\lambda(1-s)s \quad . \quad (80)$$

$$P_f = P_\lambda s^2; \quad P_t = k_{t1} P_\lambda \quad . \quad . \quad . \quad . \quad (81)$$

where $\psi = 2\pi z/\lambda$, $H_p = \dfrac{2\pi}{\lambda b}\Phi_0$, $P_\lambda = \dfrac{v_s^2 ab\lambda H_p^2}{2\times 10^{16}\rho}$, $v_s = \lambda f$, and $k_{t1} = \dfrac{w}{a}\dfrac{\rho}{\rho_t}$ where w is the total tube-wall thickness.

(7.1.2) Graded Regions at End of Pump.

(1 − cos) *form of grading over pole-pairs or wavelength at each end.*

$$\Phi = \tfrac{1}{2}\Phi_0(1 - \cos\tfrac{1}{2}\psi)\cos(\omega t - \psi) \quad . \quad . \quad . \quad (82)$$

$$H = \tfrac{1}{4}H_p[\sin\tfrac{1}{2}\psi\cos(\omega t - \psi) + 2(1 - \cos\tfrac{1}{2}\psi)\sin(\omega t - \psi)] \quad (83)$$

$$J_f = \frac{sv_s}{2\times 10^8\rho} H_p\Big[(1 - \cos\tfrac{1}{2}\psi)\sin(\omega t - \psi) - \frac{1-s}{2s}\sin\tfrac{1}{2}\psi\cos(\omega t - \psi)\Big] \quad . \quad (84)$$

$$J_t = \frac{v_s}{2\times 10^8\rho_t} H_p(1 - \cos\tfrac{1}{2}\psi)\sin(\omega t - \psi) \quad . \quad (85)$$

$$\frac{dNI_m}{dz} = \frac{5d}{2\lambda} H_p\Big[\sin\tfrac{1}{2}\psi\sin(\omega t - \psi) - (1 - \tfrac{5}{4}\cos\tfrac{1}{2}\psi)\cos(\omega t - \psi)\Big] \quad . \quad (86)$$

$$\frac{V_i}{N} = \frac{v_s b}{2\times 10^8} H_p(1 - \cos\tfrac{1}{2}\psi)\sin(\omega t - \psi) \quad . \quad (87)$$

(1 − cos) *form of grading over pole at each end.*

$$\Phi = -\tfrac{1}{2}\Phi_0(1 - \cos\psi)\cos(\omega t - \psi) \quad . \quad . \quad (88)$$

$$H = -\tfrac{1}{2}H_p[\sin\psi\cos(\omega t - \psi) + (1 - \cos\psi)\sin(\omega t - \psi)] \quad . \quad . \quad . \quad . \quad (89)$$

$$J_f = -\frac{sv_s}{2\times 10^8\rho} H_p\Big[(1 - \cos\psi)\sin(\omega t - \psi) - \frac{1-s}{s}\sin\psi\cos(\omega t - \psi)\Big] \quad . \quad (90)$$

$$J_t = -\frac{v_s}{2\times 10^8\rho_t} H_p(1 - \cos\psi)\sin(\omega t - \psi) \quad . \quad (91)$$

$$\frac{dNI_m}{dz} = \frac{5d}{\lambda} H_p[\sin\psi\sin(\omega t - \psi) + (\cos\psi - \tfrac{1}{2})\cos(\omega t - \psi)] \quad . \quad . \quad . \quad . \quad (92)$$

$$\frac{V_i}{N} = -\frac{v_s b}{2\times 10^8} H_p(1 - \cos\psi)\sin(\omega t - \psi) \quad . \quad (93)$$

Half winding over pole at each end.

$$\Phi = \tfrac{1}{2}\Phi_0[\cos(\omega t - \psi) - \cos\omega t] \quad . \quad . \quad . \quad (94)$$

$$H = \tfrac{1}{2}H_p\sin(\omega t - \psi) \quad . \quad . \quad . \quad . \quad (95)$$

$$J_f = \frac{v_s}{2\times 10^8\rho} H_p[s\sin(\omega t - \psi) - \sin\omega t] \quad . \quad (96)$$

$$J_t = \frac{v_s}{2\times 10^8\rho_t} H_p[\sin(\omega t - \psi) - \sin\omega t] \quad . \quad (97)$$

$$\frac{dNI_m}{dz} = \frac{5dH_p}{2\lambda}\cos(\omega t - \psi) \quad . \quad . \quad . \quad . \quad (98)$$

$$\frac{V_i}{N} = \frac{v_s b}{2 \times 10^8}H_p[\sin(\omega t - \psi) - \sin \omega t] \quad . \quad . \quad (99)$$

The output power P_0' and losses P_f and P_t for the three methods of end-grading are given in Table 4, where for convenience these quantities are expressed as ratios of the corresponding quantities for the ideal case.

Table 4

GROSS OUTPUT POWER AND LOSSES FOR THE THREE METHODS OF END-GRADING

	Method of end-grading		
	A	B	C
	Sum of inlet and outlet graded region only		
$k_{0e} = P_0'/P_\lambda(1-s)s$	$\frac{1}{16}\left(12 - \frac{1-s}{s}\right)$	$\frac{1}{8}\left(3 - \frac{1-s}{s}\right)$	$\frac{1}{4}$
$k_{fe} = P_f/P_\lambda s^2$	$\frac{1}{16}\left[12 + \left(\frac{1-s}{s}\right)^2\right]$	$\frac{1}{8}\left[3 + \left(\frac{1-s}{s}\right)^2\right]$	$\frac{1+s^2}{4s^2}$
$k_{te} = P_t/k_{t1}P_\lambda$	$\frac{3}{4}$	$\frac{3}{8}$	$\frac{1}{2}$
	Total for pump of n pole-pairs* or wavelengths, including mid- and graded-regions		
$k_0 = P_0'/P_\lambda(1-s)s$	$n - 2 + \frac{1}{16}\left(12 - \frac{1-s}{s}\right)$	$n - 1 + \frac{1}{8}\left(3 - \frac{1-s}{s}\right)$	$n - 1 + \frac{1}{4}$
$k_f = P_f/P_\lambda s^2$	$n - 2 + \frac{1}{16}\left[12 + \left(\frac{1-s}{s}\right)^2\right]$	$n - 1 + \frac{1}{8}\left[3 + \left(\frac{1-s}{s}\right)^2\right]$	$n - 1 + \frac{(1+s^2)}{4s^2}$
$k_{t2} = P_t/k_{t1}P_\lambda$	$n - 2 + \frac{3}{4}$	$n - 1 + \frac{3}{8}$	$n - 1 + \frac{1}{2}$

* n need not necessarily be an integer; n includes the poles in the graded region.

DISCUSSION BEFORE THE MEETING OF THE INSTITUTION HELD IN CONJUNCTION WITH THE BRITISH NUCLEAR ENERGY CONFERENCE, 25TH OCTOBER, 1956

Mr. D. A. Watt: The author presents a comprehensive survey of electromagnetic pumping principles, examines many factors which influence design and shows which of these must be considered in practical cases. I find that the influence of the magnetic field on the hydraulic loss is small in most instances, and where it would make an appreciable difference the hydraulic loss with zero field is quite trivial, so that this effect can usually be disregarded. Flux penetration in the linear induction pump, where a/λ is usually less than 0·1, can be assumed to be complete; it is limited by the current loading possible in the stators rather than by flux penetration or reactance effects, and if it is increased unduly the rate of rise of pressure becomes much too low.

The effect of field and current distortion, or 'armature reaction', in the uncompensated d.c. pump is examined at length. Since $H_i/\beta H_m = RI/V_i$ the equation for efficiency [eqn. (67)] may be expressed as

$$\eta_i = \frac{P_0}{P_0 + P_f} = 1 - \frac{RI}{RI + V_i}\beta \coth \beta$$

If $\beta \coth \beta = 1 \cdot 0$, eqn. (67) gives the efficiency of a pump operating with uniform field H_m and current density J_m. The effect of armature reaction is thus measured by the departure of $\beta \coth \beta$ from unity, which suggests that the basic parameters governing the relative influence of armature reaction are v, c and ρ. [$\beta = 2\pi vc/10^9\rho$]. The ratio H_i/H_m is certainly a pointer, but it would follow that H_i/H_m is greater for a long pump than for a short one, and so c may be regarded as more fundamental. In large pumps the loss which current and field distortion would incur can be virtually eliminated by using a compensating conductor extended suitably into the entry and exit regions. This would meet the suggested problem of over-compensation.

With regard to the proposal for low-frequency conduction pumps for bismuth, I think that careful attention should first be given to exploring the limits of size at 50 c/s. The simple half-turn pump with separate transformer may offer greater scope than the skin-depth formula suggests. An annular version of this pump with combined transformer, or near variations of this, could handle quite large flow rates. The limitation here is in the fabrication of the multiple-channel system necessary to restrict end-current losses. I think that it will be found that large flows of bismuth are most satisfactorily dealt with by the d.c. pump and homopolar generator. Homopolar generators using liquid-metal current pick-up should be capable of continuous operation with very little maintenance.

I agree with the author's main conclusions. Subject to the limits at present imposed by the effects of temperature and radiation on electrical insulation, the linear induction pumps are very convenient for large flow rates of the alkali metals. The d.c. pump, with homopolar-generator supply in large sizes, is most effective for bismuth. For all large-scale applications requiring a fairly high pressure rise it can be designed with a reasonably good power/weight ratio. When comparing the sizes of d.c. and linear induction pumping systems, the special transformer and voltage-control equipment for the latter should be taken into account. Control of a d.c. pump would be effected by varying the field of the generator.

Professor W. Murgatroyd: During the past few years many pump arrangements have been proposed to fulfil special con-

ditions, such as high pressure and high temperature, or to improve the electrical characteristics, e.g. the impedance. The author has, quite rightly, not dealt with them, since most have never been constructed, either because of the difficulties of doing so or because of lack of effort.

I think that it is worth while, however, to mention one of these, since it differs in principle from the pumps described, and offers high-head–low-flow characteristics not easily obtainable with other types. I refer to the centrifugal magnetic pump, in which the magnetic field is used to spin the liquid metal, so creating a centrifugal pressure rise. It is of historic interest, perhaps, in that the first induction pump to be built in this country was of this type; it was constructed about eight years ago and operated successfully with mercury. It consisted essentially of a disc of mercury about 1 ft in diameter which was caused to spin by a 3-phase winding. The liquid was fed in at the centre and was drawn from the periphery of this pump, and the measured performance indicated that very high pressures could be produced in a small device; in fact, operation had to be restricted by the mechanical strength of the pump. I believe that, in America, similar pumps have been built using mechanically-rotated fields.

From Section 2.5, considering the fluid dynamics of the liquid metal in the channel, I cannot see how, in practice, pressure differences of the order of 2–3 : 1 can exist. I feel sure that the fluid flow will adjust itself to equalize the pressure gradient across the channel. Will the author give more information on the usefulness of this approach in practice?

Mr. T. I. M. Crofts: The references in the paper reveal that the rapid development in electromagnetic pumps has been due to the needs of liquid-metal-cooled nuclear reactors, and it is quite likely that electromagnetic pumping practice will spread to the older-established industries when the advantages of liquid metals as coolants are fully exploited.

Mechanical pumps may be used for liquid metals, but the one advantage that has swung the balance in favour of electromagnetic pumps, in spite of their lower efficiency, is that of inherent safety. This factor has also influenced electromagnetic pumping practice in favouring induction pumps, because of the absence of the risk of channel failure due to short-circuiting the current through the walls of an empty channel.

The nuclear reactor designer has the unique problem of pumping a radioactive fluid, and therefore tends to overemphasize the safety aspect. However, if we assess how much the safety factor costs, we can then decide whether it is worth it, even under less stringent conditions. For example, one of the first of the Flip type pumps tested at Windscale had a maximum efficiency of 25% when pumping sodium–potassium eutectic and 31% when pumping sodium, while the Alip type gave comparable efficiencies of 36%–42%.

How was this improvement achieved? Since the two pumps are not of the same design, it is not possible to define a single cause, but one very evident difference was the use of a thinner-walled channel, the thickness of the stainless-steel Flip channel being 0·064 in and that of the Nimonic Alip channel 0·020 in. Some reduction in the thickness of the circular channel is acceptable because of the improved mechanical strength over the flat channel, and the higher electrical resistivity of Nimonic is advantageous. But have we sacrificed safety for improved performance? We have 400 gal/min of sodium–potassium at 200°C flowing at 30 ft/sec in a duct whose thickness is that of the feeler gauge used to set the plug gaps in a motor car.

How much do we save by this improved efficiency? Consider two 400 gal/min Alips pumping sodium–potassium, one on the basis of the figures in Section 2.6 of the paper and the other of 25% efficiency, having a thicker duct. The main saving will be in operational costs. For one year's operation (8 760 hours) the saving is £200, which may be of the order of the annual premium for safety. Is it worth it?

Mr. A. S. Fenemore: The author points out that the winding of flat-type induction pumps can be placed on either side of the pump channel, so improving the uniformity of the field. It may be possible also to use partly closed slots, with further benefit to field uniformity and the advantage of higher gap permeance. In annular pumps it is essential to use open slots. Linear pumps operate as induction motors with very large air-gaps, so that the increase in gap permeance due to partly closed slots may be worth while. In any induction pump it is essential to work with the highest possible electrical loading, to obtain a reasonable working flux-density in the liquid metal, and therefore a compact unit. This leads to the use of deep and wide slots; the deep slots give low power-factor, and the large gap gives low useful flux. The result is that the leakage flux may be of the same order as, or even exceed, the useful flux, which is in marked contrast to normal electrical machines.

The author mentions that the winding leakage reactance of the flat pump is lower than that of the annular type: it is, in fact, considerably lower. With the same basic design for both, the annular pump needs about twice the slot depth to give about the same total cross-section of slot copper, which means that the annular design has nearly twice the slot leakage flux and that the slot-winding leakage reactance is nearly four times as great. In practice, the optimum basic designs for a given duty for flat and annular pumps may differ somewhat, but it seems clear that the annular pump will, in general, have a lower power-factor than the flat pump.

In flat-pump designs the reaction from the pressure within the pump tube may be dealt with in two ways, namely by the use of a thin-wall tube, with the pressure reaction taken by bolting or clamping the cores together, or by using thicker walls and internal webs to give a self-sustaining tube, which will withstand both pressure and vacuum. The webs would normally be pierced to minimize the resistance of the paths of the currents induced in the liquid metal. This tube design gives some decrease in pump efficiency, but greatly increased robustness and reliability.

I agree with the author that the highest fluid velocity should be used, and that it should be increased to the value where hydraulic loss begins to affect efficiency. The only specific value given in the paper is 25 ft/sec for the 420 gal/min annular design, but higher velocities can presumably be used. Is there a limiting velocity for a given fluid, and, if so, what is its value for sodium? What material is used for the pump tube of the pump handling bismuth at 500–550°C?

Mr. W. B. Woollen: I agree with the author's summary at the end of the paper, with one or two provisos. For sodium there seems to be very little choice, and the induction pump has really no competitor. A point to be borne in mind, however, is that we are interested in pumps very much larger than any which have been considered in detail so far. For power-type reactors we are interested in pumps with capacities up to 10 000 gal/min, and for these the arguments for and against various types might change slightly. I think it quite feasible to make satisfactory pumps of this size, but should like the author's comments, particularly in view of the reliability of pump channels.

For the larger sizes of pump for high-resistance liquid metals there seems little alternative to the d.c. types, which have quite serious disadvantages. For instance, they involve the use of busbars, and if these have to be of any length the weight of the copper involved is considerable. Will the author amplify his comments about the large d.c. pumps and say whether it is possible to avoid them? He suggests, for example, the low-frequency type of pump. Could this be developed in large sizes for the high-resistance liquid metals, or is it possible to develop

satisfactory rotating-field type of pump in which the field is nerated by mechanical means outside the pump?

Mr. A. B. J. Reece: In his remarks on pulsating components core flux in linear induction pumps the author implies that the fect on losses and efficiency would be the same in both the nnular and the flat versions. It is, however, only in the annular ersion that the tube walls and the liquid metal form short-rcuited turns linked with the pulsating component of the core ux; in the flat pump the tube-wall and the liquid-metal e.m.f.'s e dependent only on the gap field conditions. Consequently a ulsating component of core flux produces extra eddy-current sses only in the annular form. This is supported by measure-ents made on a flat pump having no end grading. The easured efficiency was 20%. When stator I^2R, tube-wall, ydraulic and iron losses are allowed for, the estimated ideal ficiency is 40%, compared with 18% given in Fig. 8. It is nown in this case that there was a considerable pulsating com-onent superimposed on the travelling gap field.

The assumption with regard to magnetizing-current distribu-on made in deriving eqns. (16)–(18) means that they are not rictly applicable to the practical case of an annular pump on ad and operating from a balanced polyphase supply.

Simple half-winding of the end-poles does not produce the gap eld condition defined by eqn. (21) and does not eliminate the ulsating component of core flux from the middle region of the ump. Therefore, the expressions in column C in Table 4 are ot valid for simple half-wound end-poles, even for annular umps. The reason for the adoption of half-winding of the end-oles of flat pumps is that, when used in conjunction with an dd number of fully wound poles, the undesirable pulsation in e gap field is eliminated.

Mr. D. T. Shore: I have used the small a.c. conduction pump ery successfully, and have operated experimental circuits at a emperature as high as 650° C over a considerable period. This ggests a very high standard of reliability for pumping equip-ent, and I cannot think of a mechanical pump which would perate at this temperature. Electromagnetic pumps with apacities exceeding 20 gal/min are very expensive; hence liability may be the single factor that can rule out the mechanical pump. At 50 gal/min the price difference is a factor of between 5 and 8 in favour of the mechanical design.

A pump failure may lead to a small leakage at the pump (tolerable for a period to maintain circulation) or it may, by stopping circulation, cause a major plant failure due to over-heating. The former case is not a disaster; it is just a continual maintenance trouble, which is never welcome in any commercial plant or equipment.

For large duties the induction pump is rather limited in the temperature at which it can operate, because of the insulation problem. We can blow pumps with compressed air, but even so it is stated that 650° C would be a very high temperature, and for this it would seem that the conduction pump, where it is possible to keep the windings well away from the hot material, has an advantage. The author, however, suggests a type of pump for larger plants to operate at high temperatures with two opposing factors, namely a low-temperature pump or a low efficiency. I do not think that the efficiency of the pump is so important in designs of heating circuit using various high-temperature media. The pump is seldom chosen for some optimum efficiency. It may be liked for its glands, its bearings and so on. Very few people ever check the power input of a mechanical pump, but everyone checks an electromagnetic pump. I think that the operating efficiencies would not be very different.

The main weakness of the electromagnetic pump lies in the thin-wall channel in current designs. This is usually the thinnest part of the circuit, and for mild-steel circuits leaves a joint problem which, while it can be solved, is preferably avoided.

Mr. R. H. Phillips: I have recently encountered problems in the mixing of liquid metals of different densities at temperatures in the region of 1 100–1 500° C. Professor Murgatroyd refers to pumps which will withstand temperatures considerably above the 300–350° C which has been mentioned, and Mr. Shore mentions 650° C. What are the possibilities of extending this to, say, 1 250° C, which would open up a very interesting field?

[The author's reply to the above discussion will be found overleaf.]

NORTH-WESTERN CENTRE AT MANCHESTER, 6TH NOVEMBER, 1956

Mr. R. R. Matthews: In reactor work it is essential that the olant is not lost by leakage or rupture of pipes or equipment, nd therefore the heat-removal circuits are designed and built a very high standard. For instance, stainless steel is used roughout sodium circuits, which are butt-welded and fully adiographed, pressure tested and leak tested. The pump duct an form the weaker part of the circuit, particularly if it is flat, nd therefore it must be fabricated to the same high standard nd strengthened as necessary. Another essential is that coolant ow must be maintained whenever the reactor is operating and erefore the windings must be of sound and durable construction.

A second requirement is for the pump to operate at a high emperature. It is usually fitted into the coolest part of the ircuit, but with a single-stage steam cycle the maximum steam ressure is limited by the minimum temperature to which the odium must be cooled. This is fixed by the maximum tem-erature at which the winding insulation can operate unless orced cooling is adopted, but it is undesirable to do this, since dditional equipment is introduced and this decreases the eliability. What improvements can be expected in the near uture which will allow windings to operate at temperatures higher han at present, since this forms one of the major limitations for he future use of electromagnetic pumps?

Another requirement is that the pumps shall operate satisfactorily in a region of high γ-flux; again, the item most likely to be affected is the insulation.

A fourth requirement is that for pumps fitted into active sodium circuits there must be means of removing windings by remote control. This can be fairly easily achieved for the Flip type, and the author suggests that this can also be done for the Alip type. Previously this had been considered to be a major drawback when considering the use of the Alip.

When the above requirements have been met the choice of type of pump will be based on efficiency and cost, and in view of the possible development of mechanical pumps it is essential that efforts be made to increase the one and lower the other. A point to consider here is that a large percentage of input energy is lost by cooling. If natural cooling is used, the heat flows from the windings to the sodium and is therefore recovered as it raises the temperature of the sodium. The effect of this is to increase the overall efficiency of the pump when compared with a mechanical pump, since very little of the energy lost in this is recoverable. With regard to cost, it has been considered that 18 : 8 : 1 austenitic stainless steel must be used for sodium circuits, but consideration is now being given to the use of some of the low-alloy steels. Could a steel cheaper than stainless be used for the electromagnetic pump duct?

For future large-scale sodium-cooled reactors, pumps with

outputs of 6000–10000 gal/min may be required; what does the author consider to be the most suitable and competitive type of pump for this duty?

Mr. E. R. Laithwaite: All types of induction pump are examples of 'short stator' machines, i.e. machines in which the travelling wave of magnetomotive force produced by the stator is discontinuous. A recent paper* discloses a theory of the behaviour of such machines and evaluates the extra losses due to the transient phenomena associated with each end of the stator.

If the machine is considered from the constant-current concept the flux density at the end of the stator at which liquid enters the pump is shown to be virtually zero for small values of slip. The flux distribution under the block is dependent upon the slip and the number of poles on the block, n. At a slip of $1/(n+1)$ the extra losses associated with the entry end can be shown to be zero. At a slip of $2/(n+2)$ the losses associated with both edges can similarly be shown to be negligible, both these statements depending on the assumption that the rotor time-constant is large compared with the period of the supply. These results may be summarized by saying that, if the stator is series-connected, the flux will grade itself under the block and the necessity for special end-coils is removed, since the machine can be designed to run on load at the slip appropriate to the advantageous flux grading.

The calculations in Section 2.8, relating to the spiral pump, indicate that the result of constraining the liquid to move at an angle to the direction of motion of the field is to lower the effective synchronous speed and the efficiency. This is true only for the order of dimensions used in the pumps described. A recent paper* has shown that, if the pole pitch is small compared with the pole width, a speed increase results. The same paper describes a system for a continuously-variable-speed induction motor using this principle. The latter might well be applied to the liquid-metal pump for producing variable pumping speeds with constant efficiency. Can the author give an indication of the possible demand for such a system?

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Dr. L. R. Blake (*in reply*): Mr. Watt questions whether H_i/H_m and β most appropriately describe the parameters which control armature reaction in the conduction pump. An understanding of the mechanism involved is made clearer by an iterative calculation, which, incidentally, is more accurate than the analytical method given in the paper since it takes into account flux and current fringing. This method has been described briefly by the author† and consists of starting the calculation with a field distribution $H_1(z)$ and a current density distribution $J_1(z)$, as occurs in the absence of any interaction between them. Owing to J_1, however, the field is distorted by ΔH_1 to H_2, and this in turn produces a further distortion of J_1 to J_2, which in turn changes H_2 to H_3 and so on, the calculation being repeated until the changes produced are negligible. This approach simplifies the principles involved and, it is considered, supports the choice of controlling parameters.

The number of types of electromagnetic pump are quite legion, but the paper concentrates on what appeared to be the basic types which were capable of covering a wide range of pressure and flow conditions and a range of liquids. This is not to deny the importance of other pumps, such as those described by Prof. Murgatroyd. In particular, the range of pumps with mechanically rotated magnetic fields are an important class deserving special attention. Section 2.5 was not intended to show that pressures of the order of 2–3 atm can exist across the duct, but that this is the order of the pressure which will cause liquid circulation: the problem is difficult to solve other than in two stages in this way. In most practical designs of pump the effects of limited current penetration, as calculated in Section 2.5, can be neglected.

As Mr. Crofts points out, the walls of the annular pump were 0·02 in thick, and although this is undoubtedly small, it should be adequate provided that the liquid metal circuit is designed to limit the longitudinal stresses applied to the tube; since the tube itself is only 4 in in diameter, it is capable of a high internal pressure. Nevertheless, there is not a great deal to lose in increasing the thickness, but it should not be necessary with a circular tube to increase it to the value necessary in a Flip. Also, in general it is not necessary to make the inner tube as thick as the outer; but even if both the inner and outer tubes of the Alip were increased to 0·064 in the efficiency would drop only to 37 and 32% with sodium and sodium–potassium respectively.

I have never found a case where the use of semi-closed slots, as suggested by Mr. Fenemore, has been desirable. Certainly, a winding on one side of the duct has four times the slot leakage reactance of a winding with the same total slot depth on both sides of the duct, but this is not the complete story in comparing the Flip and the Alip: in the Alip the channel width would be a little less, owing to slots on one side; the gap permeance is higher, heat insulation is on one side of the duct only and there is no additional leakage reactance due to the overhanging portion of the winding. The maximum liquid velocity desirable in large sodium pumps can exceed 40 ft/sec, but these velocities may not be permissible for other reasons, such as the need to limit mass-transfer effects. Chrome-steels so far appear the most suitable for bismuth at 500° C.

Taking the comments of Mr. Woollen and Mr. Matthews together, it must be mentioned that my practical experience has been limited to Alips and may therefore be biased in their favour with respect to the Flip. However, it would appear that, for pumps with capacities of the order of 10000 g.p.m., flat channels and their associated diffusers would be the more difficult to manufacture and the co-axial or re-entrant flow type of Alip with removable winding would appear the more suitable. Low-frequency pumps would appear to have several important advantages over d.c. pumps in reactor applications using bismuth, and it should be practicable to build a low-frequency conduction pump with a capacity of up to several thousand gallons per minute. The mechanically rotating field type is free from some of the restrictions of the induction pump and presents another possibility. For high-temperature radio-active conditions it seems likely that the most promising insulating materials are the inorganic insulations, particularly asbestos, glass and ceramic. The requirement limiting the choice of steel for the pump duct of an induction pump for sodium is that it should be non-magnetic; of lesser importance is that it should have a high resistivity, and it should be resistant to sodium; these restrictions are quite severe and no cheaper alternative to 18/8/1 has so far appeared practicable.

I agree with Mr. Reece that the annular and flat forms of pump have differences in the theory of their operation. In order that the theory presented shall be applicable to both, the most important qualification, which makes eqn. (8) valid for the Flip also, is that it should have infinite conducting side-bars which extend beyond the length of the pump. The fact that a

* Williams, F. C., Laithwaite, E. R., and Piggott, L. S.: 'Brushless Variable-Speed Induction Motors', *Proceedings I.E.E.*, Paper No. 2097 U, June, 1956 (104 A).

† B.T.H. Third Summer School in Electrical Engineering, July, 1956.

* Williams, F. C., and Laithwaite, E. R.: 'A Brushless Variable-Speed Induction Motor', *Proceedings I.E.E.*, Paper No. 1737 U, November, 1954 (102 A, p. 203).

test of an uncompensated Flip did not show agreement with Fig. 8 is not surprising, for, apart from these assumptions not being valid, it is difficult in practice to realize a pure sinusoidal travelling wave of magnetizing current, which is the limiting assumption used in deriving eqns. (16)–(18). Simple half-winding of end-poles does very approximately give the field of eqn. (21) and, without resorting to extremely tedious calculations, it should serve to show the order of usefulness of the arrangement.

In reply to Mr. Phillips, there seems little hope of extending operating temperatures of electromagnetic pumps to as high as 1 250° C.

Mr. Laithwaite's work on short-stator machines is most relevant to linear induction pumps, and should be helpful in finding optimum end-grading arrangements and how they differ at inlet and outlet for differing values of slip, particularly with series-connected windings. The continuously-variable induction-motor principle appears likely to have little advantage applied to electromagnetic pumps.

DISCUSSION ON
'THE NON-DESTRUCTIVE TESTING OF ELECTRIC STRENGTH OF LIQUIDS'*

Mr. J. Wainwright (*communicated*): I was interested in the statement that the equipment has proved eminently suitable for routine oil testing, mainly because the new apparatus does not appear to conform to the spirit of the British Standard which is used for the majority of routine tests. Appendix G of B.S. 148: 1951 requires—presumably mandatorily—that the testing set shall be capable of producing an arc through the oil with a current of at least 20 mA.

No figures are given in the paper for the currents produced during breakdown, but it is obvious that the total current (from source and self-capacitance) cannot approach the 1 amp or so suggested by the Standard. Further, the discharge can probably be described as a spark rather than an arc. It would therefore be interesting to have the author's views on the importance of this requirement, bearing in mind that it has been a feature of the Standard for more than 20 years.

The Standard also makes special mention of preliminary transient sparking prior to breakdown. It is agreed that in practice a sample of oil exhibiting such sparking would be regarded with considerable suspicion, but it is interesting to note that, whereas the Standard advises that the occurrence be disregarded, the new apparatus may register it as a failure.

Referring to the results given in Tables 2, 3 and 4 of the paper, it is a pity that more information is not given on the statistical distribution of the results. Few papers appear nowadays on the electric strength of liquids without including at least the means and the standard deviations of the test values.

Another point is that it is difficult to compare the results in Tables 2 and 3 with those in Table 4, either because different gaps are used or because of a different method of presentation.

Some further information would be welcomed on the degassing techniques used. Is it to be assumed that the results in Table 3 and 4 were obtained on samples degassed by the same method? The mere reduction of the gas pressure above a sample of oil at room temperature is a particularly ineffective way of removing the dissolved gases.

Mr. W. P. Baker (*in reply*): I must agree with Mr. Wainwright's claim that the new equipment does not conform to the spirit of the British Standard, if by that he means that an arc is not maintained through the oil. This is not surprising, because it was the removal of this very feature of the old test that was sought in the new design.

However, the figure of 20 mA at the required proof voltage of 40 kV has been borne in mind in choosing the values of the limiting resistors (the 1 amp suggested in B.S. 148: 1951 was interpreted as being an upper limit rather than an ideal). This consideration assumes that the arc path through the oil is of negligible resistance compared with 2 megohms; if it were so desired, however, the values of the limiting resistance could be halved (most conveniently by omitting resistor R_2 in Fig. 2 of the paper) without impairing the working of the equipment.

It is worth while considering just what has been done by reducing the source impedance. If we assume that the delay in short-circuiting the specimen is 4 microsec, as stated in Section 6 of the paper, then the average current flowing in the breakdown path due to the discharging of a self-capacitance of $5\,\mu\mu F$ is 70 mA at a breakdown voltage of 40 kV (r.m.s.). The current supplied from the source is only $\frac{2}{7}$ of this value, and doubling the source current is not likely to affect the breakdown conditions by a measurable amount. This is borne out by the test results given in Table A.

Table A

OIL TESTED BETWEEN 13 MM BRASS SPHERES SPACED 4 MM APART AT 20° C

Source impedance	Mean breakdown voltage (mean of 30 tests)	Standard deviation
megohms	kV	kV
2	32·8	3·9
1	33·0	3·4

Clearly, the question of the ability of the testing set to maintain an arc of 20 mA is worthy of further discussion.

I cannot agree that the absence of information on the statistical distribution of test results detracts from the value of Tables 2, 3 and 4 of the paper. The results of Tables 2 and 3 lie on smooth-falling curves, and those of Table 4 lie about a horizontal line; together, the results support the conclusion that oil has a breakdown-voltage/time characteristic whose steepness depends on the amount of gas in solution. Further information is irrelevant.

I agree with Mr. Wainwright's final statement. It must not be assumed that the titles of Tables 3 and 4 are synonymous. The oil was de-gassed by foaming it through a sintered glass filter at a pressure of 1 mm Hg and a temperature of 20° C.

* BAKER, W. P.: Paper No. 2146 M, August, 1956 (see 103 A, p. 337).

621.314.214

Paper No. 2203
Feb. 1957

THE MOVING-COIL REGULATOR: A TREATMENT FROM FIRST PRINCIPLES

By Prof. G. H. RAWCLIFFE, M.A., D.Sc., Member, and I. R. SMITH, B.Sc., Graduate.

(*The paper was first received* 28*th May, and in revised form* 28*th July*, 1956.)

SUMMARY

A particular type of moving-coil regulator, of exceptional ingenuity, has found wide application over the last fifteen to twenty years, but it is believed that no rigorous analysis of it has previously been carried out. Besides being rigorous, it is thought that the theory here given also facilitates calculations on the performance of the regulator, and test results have shown that the theory is fully and closely supported by practical performance.

LIST OF SYMBOLS

I_1 = Input (magnetizing) current on no load.
I_3 = No-load current in moving coil.
I_L = Output load current.
I_B = Additional input current on load.
$I_1 + I_B$ = Total input current on load.
I_S = Additional current in moving coil on load.
$I_3 + I_S$ = Total current in moving coil on load.
V_1 and V_2 = No-load voltages on upper and lower halves of main winding.
V_1' and V_2' = Load voltages on upper and lower halves of main winding.
V = Applied line voltage.
L_1 = Self-inductance of each half of main winding.
L_3 = Self-inductance of moving coil.
M_1 = Mutual inductance between two halves of main winding.
M_2 = Mutual inductance between upper half of main winding and moving coil.
M_3 = Mutual inductance between lower half of main winding and moving coil.
Z_1 and Z_2 = Lumped impedances of upper and lower halves of main winding measured on no load.
Z_3 = Lumped third impedance of equivalent T-network.
Z_0 = Equivalent (Thévenin) output impedance.
(M_2, M_3, Z_1, Z_2, Z_3 and Z_0 all vary with moving-coil position.)
N_1 = Number of turns in each half of the main winding.
N_3 = Number of turns in the moving coil.
Z_L = Impedance of load.

(1) INTRODUCTION

One of the most ingenious dynamo-electric inventions of the last twenty years is a moving-coil regulator described[1] in 1938. The present authors have found such regulators to be of the greatest help in the laboratory, and a large number have been used for very varied purposes all over the country. The engineering aspects of the regulator, as described in the original papers by Norris,[1,2,3] are of the utmost interest and value; but the treatment there given is declared to be approximate, and requires the background of knowledge of an expert transformer designer for its full appreciation.

The authors have therefore prepared a new account of this regulator based on the fundamental principles of electrical science. This treatment is believed to be both rigorous and in a form acceptable to the non-specialist, since it requires for its understanding only general scientific training, rather than specialized knowledge of regulator and transformer design.

(2) THE PROTOTYPE MOVING-COIL REGULATOR

The moving-coil regulator in its simplest terms contains only two independent windings: the main winding and the short-circuited moving coil. The main winding consists of two equal concentric-type transformer coils, wound in opposed senses and connected in series, mounted symmetrically on a transformer-type core. The primary voltage is applied to these two coils in series, and the output is taken across one of them, here assumed to be the lower coil.

A further concentric coil, of length comparable to one of the main coils and of inside diameter slightly larger than their outside diameter, is arranged to be movable up and down outside the main coils. This moving coil is permanently short-circuited; though in experimental equipments the ends of the coil are brought to linked terminals, so that an ammeter may be inserted for test purposes. The whole arrangement is shown diagrammatically in Fig. 1.

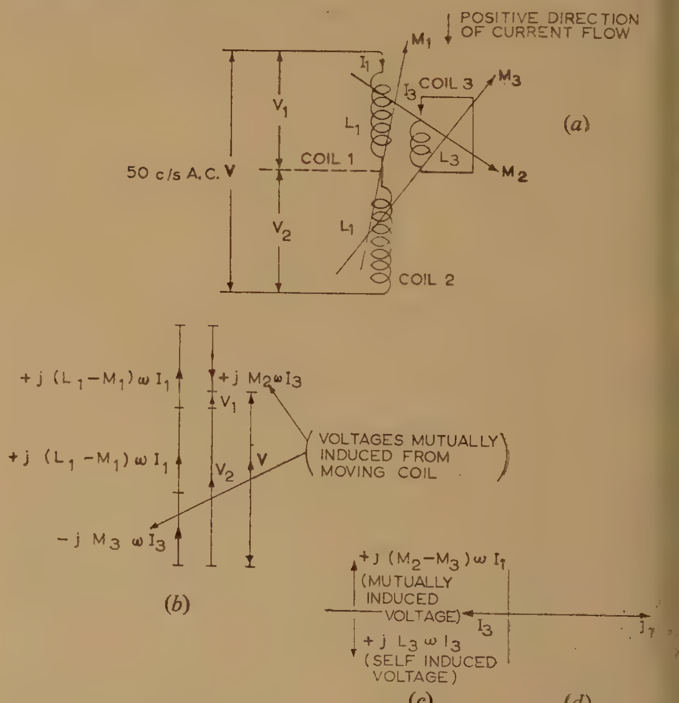


Fig. 1.—Circuits and vectors on no load.

(*a*) Circuit layout and constants.
$V_1 < V_2$
$M_2 > M_3$
$(M_2 - M_3)$ is positive
I_3 is controlled in direction by M_2. $+j = 90°$ (anti-clockwise).
(*b*) Voltage vectors in fixed coils.
(*c*) Voltage vectors in moving coil.
(*d*) Current vectors.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
Prof. Rawcliffe is Professor of Electrical Engineering, University of Bristol.
Mr. Smith was formerly at the University of Bristol, and is now with the General Electric Co., Ltd.

In the practical application of the regulator, further windings are very often included, transformer-coupled to either or both halves of the main winding and interconnected in various ways, as described by Norris;[3] but these further windings and connections add nothing to the principle of the regulator, and are therefore not discussed here. The discussion is confined to the arrangement shown in Fig. 1, which is the heart of the whole matter, and which will throughout the paper be described as a regulator.

Three-phase moving-coil regulators consist of three independent single-phase units mechanically coupled together, with a single drive for the three moving coils, but there is no magnetic linkage between the phases. In principle, therefore, it is only necessary to consider a single-phase regulator, as in Fig. 1.

The fact that the two halves of the main winding are wound in opposite senses has the fortunate consequence that the mechanical forces on the moving coil tend to neutralize one another as shown in Section 4.8, and the resultant force is much smaller and the moving coil is easily shifted up and down. The fact that these forces nearly cancel is, however, only one reason for using opposed winding senses, this arrangement being for many reasons helpful to the proper and efficient operation of this regulator. For example, it is the opposed winding senses which make easily possible an almost uniform 100% voltage range, as discussed in Section 4.1, and which very much decrease the no-load current in the moving coil.

(3) THE ACTION OF THE REGULATOR

The magnetic fluxes due to the two main coils necessarily flow largely in air paths, as shown in Fig. 2, because no net flux can

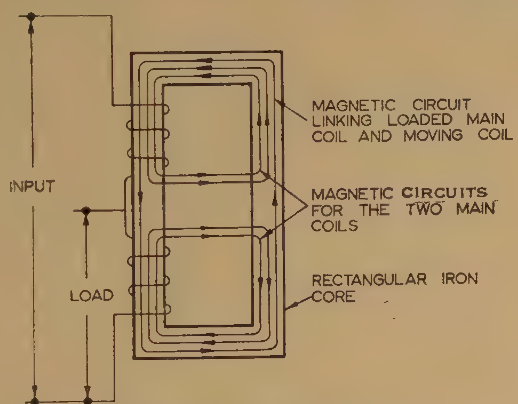


Fig. 2.—Magnetic circuits of regulator.

be set up round the transformer core as a result of these two opposed coils. If the short-circuited moving coil is so placed as to be closely linked with one main coil, and much less linked with the other, the applied voltage will, on any reckoning, mostly appear on the unlinked main coil, and only a small voltage will appear on the linked main coil. The linked main coil acts rather like a transformer on short-circuit; the unlinked rather like a transformer on open-circuit, the two transformer primary windings being connected in series. As the moving coil is transferred from being linked with one main coil to being linked with the other main coil, the voltage is gradually redistributed between the coils.

This is an over-simplified account of the action of the regulator, however, and it ignores the mutual induction between the main coils; and it would never suggest, as is in fact the case, that the whole of the applied voltage can appear on one main coil: indeed, the voltage on one main coil may exceed the total applied voltage. The theoretical basis of this possibility is, however, made absolutely clear in Section 4.1.

(3.1) Current in the Moving Coil on No Load

The first important difference between a transformer and the regulator is that the moving coil must be short-circuited even on no load, as it is the current in the moving coil which determines the no-load voltage distribution between the two halves of the main winding.

When the moving-coil regulator was first introduced, the idea of a permanently short-circuited coil, which is instinctively associated with heavy currents and large forces, inevitably caused incorrect allegations to be made about its performance. It was perhaps natural, in such a context, that the inventors of the regulator should have stated that there was no current in the short-circuited coil at no load for any regulator position, though strictly the current is not zero, but merely small compared with the rated load current. It has therefore a negligible effect on the regulator rating, but scientifically this no-load current in the moving coil entirely determines the action of the regulator, and causes the unequal distribution of voltage between the two halves of the main winding. Only in its middle position is the no-load current in the moving coil zero, and then the voltages on the two halves of the main winding are equal.

The no-load performance of the regulator in a typical case is as shown in Fig. 3. It will be seen that the range of variation of magnetizing current is relatively small (about 12% in this case); but, in principle, as the vector equations will show, the magnetizing current is not constant. The limited range of its variation is due to a particular combination of circuit parameters and not in any way to the inherent necessities of the system; and though the current in the moving coil is often smaller than the magnetizing current (at the maximum, about 20% of it in the particular case shown in Fig. 3), its range of variation is very wide—from zero to full value over each of the two halves of its travel. The current, both on no load and on load, in the moving coil is increased if the number of turns in it is reduced (see Sections 4.1 and 4.4), the ampere-turns of the moving coil remaining nearly constant for any given load.

(3.2) Current in the Moving Coil on Load

On load, the moving coil carries a further current which completely swamps the no-load current numerically, just as the load current swamps the magnetizing current in a normal transformer. It would really be correct to say that on no load there are two magnetizing currents in the regulator, one in the moving coil and one in the main winding; and in many senses the moving coil is more properly regarded as an auxiliary primary winding, inductively fed, rather than as a short-circuited secondary winding.

When the moving coil is regarded as an extra primary winding it becomes natural that, on load, it should provide the additional ampere-turns, to balance the ampere-turns due to the load current, in the same way as a primary winding normally does. That this happens is shown by theory in Sections 4.3 and 4.4 and was confirmed by many tests. Since the main primary winding of the regulator cannot exert any net ampere-turns on the main magnetic circuit, the extra primary winding does so instead. Further, when the moving coil is regarded as an extra primary winding its no-load current could be expected to be comparable with the magnetizing current rather than with the short-circuit current.

(3.3) Primary Current on Load

The input current cannot be calculated, as for an ordinary transformer, by taking it to be the ampere-turn balance of the

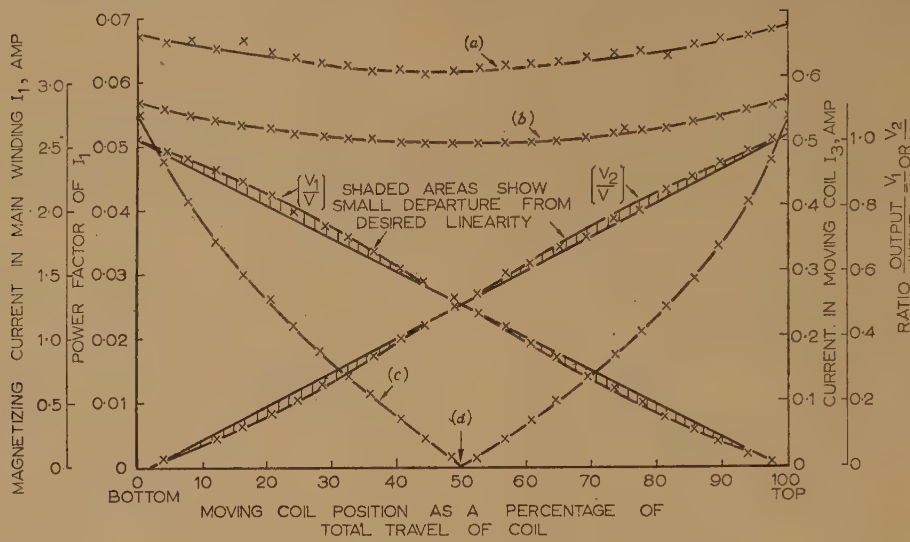


Fig. 3.—No-load performance of typical small regulator for 230 volts 50 c/s single phase.

(*a*) Power factor of I_1.
(*b*) Magnetizing current in main winding, I_1.
(*c*) No-load current in moving coil, I_3.
(*d*) Point of phase reversal of I_3.

output current; because, as explained, the output ampere-turns have already been balanced by the current in the moving coil. A new electromagnetic 'mechanism' has, therefore, to be conceived to explain the reaction of the output load current on the input circuit. Plainly, its magnitude must be such that, after taking account of losses, the input power is equal to the output power; but, whilst this gives the correct result, it does not obviously explain how the current drawn from one-half of the main winding can give rise to another current in the entire main winding, even though the latter can exert no net ampere-turns on the iron core. In Sections 4.2–4.8 the reaction on the supply of a load impedance Z_L, connected across the lower half of the main winding, is fully considered.

(4) NEW THEORETICAL ANALYSIS OF REGULATOR

(4.1) No-Load Voltages

The proper approach to this problem is to consider the regulator, as shown in Fig. 1, as two reactances in series, the circuit constants being given in the diagrams. The whole arrangement forms, in effect, a reactive potential divider, and Fig. 1 shows the idealized regulator and the corresponding current and voltage vectors, when the moving coil lies towards the top of its motion.

In drawing these diagrams it is necessary to adhere to consistent current conventions; the ones chosen being that current flowing downward in coil 1 gives a positive self-induced voltage V_1, that current flowing downward in coil 2 gives a positive self-induced voltage V_2, and that the signs of the remaining voltages are adjusted with respect to these conventions. It is further assumed that, when coils 1 and 3 are more closely coupled than coils 2 and 3, currents in anti-phase will flow in the same direction in both coils.

From consideration of these diagrams and circuit conventions, the vector equations for the regulator on no load can be written as follows:

$$V_1 = j[(L_1 - M_1)I_1 + M_2I_3]\omega \quad . \quad . \quad . \quad . \quad (1)$$

$$V_2 = j[(L_1 - M_1)I_1 - M_3I_3]\omega \quad . \quad . \quad . \quad . \quad (2)$$

$$0 = j[L_3I_3 + (M_2 - M_3)I_1]\omega \quad . \quad . \quad . \quad . \quad (3)$$

$$V_1 + V_2 = V \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

These equations, after suitable manipulation, give the followin results:

$$I_3 = -I_1\frac{M_2 - M_3}{L_3} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$\frac{V}{I_1} = j\left[2(L_1 - M_1) - \frac{(M_2 - M_3)^2}{L_3}\right]\omega = Z_1 + Z_2 \quad . \quad (6)$$

$$\frac{V_1}{I_1} = j\left[(L_1 - M_1) - \frac{M_2}{L_3}(M_2 - M_3)\right]\omega = Z_1 \quad . \quad (7)$$

$$\frac{V_2}{I_1} = j\left[(L_1 - M_1) + \frac{M_3}{L_3}(M_2 - M_3)\right]\omega = Z_2 \quad . \quad (8)$$

and hence

$$\frac{V_1}{V} = \frac{(L_1 - M_1) - \left(\frac{M_2}{M_2 - M_3}\right)\left[\frac{(M_2 - M_3)^2}{L_3}\right]}{2(L_1 - M_1) - \left[\frac{(M_2 - M_3)^2}{L_3}\right]} \quad . \quad (9)$$

and

$$\frac{V_2}{V} = \frac{(L_1 - M_1) + \left(\frac{M_3}{M_2 - M_3}\right)\left[\frac{(M_2 - M_3)^2}{L_3}\right]}{2(L_1 - M_1) - \left[\frac{(M_2 - M_3)^2}{L_3}\right]} \quad . \quad (10)$$

Eqn. (5) gives the no-load current in the moving coil as

$$I_3 = -I_1\frac{M_2 - M_3}{L_3}$$

and it will be observed that an increase in the number of turn in the moving coil will increase the numerator of this expressio nearly in direct proportion, but will increase the denominator a the square of the number of turns. It thus follows that, for given magnetizing current I_1, the no-load current in the movin

l I_3 will be inversely proportional to the number of its turns: fact, the moving coil exerts a given number of ampere-turns order to cause the action of the regulator, and these ampere-ns can arise from coils of differing numbers of turns. There no absolutely correct number of turns for the moving coil, :n when the main winding is fully determined.

The condition that V_1 shall be able to take a value equal to V, even greater than V, can be expressed either as

$$\frac{V_2}{V} \leqslant 0 \quad \text{or as} \quad \frac{V_1}{V} \geqslant 1$$

is will occur when the moving coil is at the bottom of its travel, which position $M_3 > M_2$. Eqn. (9) or (10) then shows that : exact condition for this is that

$$L_1 - M_1 \leqslant \frac{M_3(M_3 - M_2)}{L_3} \quad . \quad . \quad . \quad (11)$$

ıce M_3 and M_2 are both nearly proportional to N_3, and L_3 to , the value of the right-hand side of eqn. (11) is nearly inde-ndent of N_3. This invariant value may therefore be found by suming that N_3 is changed to be equal to N_1. M_3 and L_3 ll then become very nearly equal, but M_3 and M_2 will be anged in the ratio r; and the right-hand side of eqn. (11) will :n be equal to $r(M_3 - M_2)$, where $r = N_1/N_3$.

Eqn. (11) may therefore be rewritten, very nearly, as

$$L_1 - M_1 \leqslant r(M_3 - M_2) \quad . \quad . \quad . \quad . \quad (12)$$

ıis then shows that, provided that a suitable proportion is tained between the various circuit parameters, it is possible r the voltage on one half of the main winding to rise at least to, if not above, the line voltage. This is contrary to what ould have been inferred from the simple theory, which com-res the regulator to an open-circuited transformer in series th a short-circuited transformer, the latter theory ignoring the ıtual coupling between the two primary windings.

The essence of design for the greatest possible voltage range is erefore that the mutual coupling M_3 between the moving coil ıd one fixed coil, at the end of travel, shall substantially exceed at between the moving coil and the other fixed coil M_2; and at the mutual inductance, M_1, between the two halves of the ain winding shall be as near to the self-inductance, L_1, of each is consistent with maintaining the difference between M_3 and I_2 at the end of travel.

This condition can clearly be fulfilled where the main winding onsists of two concentric-type coils, end-to-end on the same ore, with a concentric moving coil outside them. It cannot be lfilled with a pancake coil moving up and down between two ırther parallel pancake coils, as this design prevents close oupling between the two halves of the main winding. The ırlier forms of this regulator which used pancake coils were not, ı fact, able to obtain the full range of voltage.

(4.2) Load-Current Ratios

As explained in Section 3.3, it is impossible to calculate the ıput current from the output current by a simple ampere-turn alance, as for an ordinary transformer.

On no load, as explained in Section 4.1, the regulator is, in ffect, a complex reactive network, which divides the applied oltage V into two components V_1 and V_2; and the imposition of load will alter the distribution of potential across the network.

The network is represented in Fig. 4 by an equivalent T-circuit vith load impedance Z_L added, as it is well known that any pas-ive network between two pairs of terminals can be so represented. t is convenient to treat the total input current $(I_1 + I_B)$ as omposed of two components: I_1, the magnetizing current, and

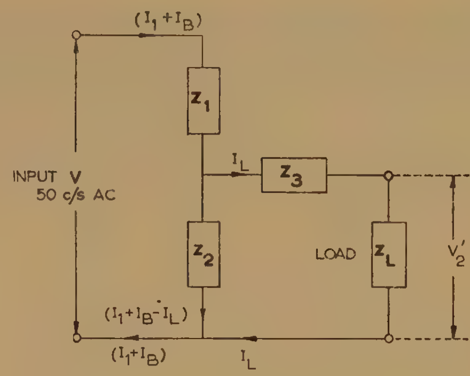


Fig. 4.—Equivalent T-network for regulator.

I_B, the additional input current component, which flows when an output current I_L is drawn from the lower half of the main winding through the load impedance Z_L.

Referring to Fig. 4, the no-load and load equations, respectively, may be written as

$$V = I_1(Z_1 + Z_2) \quad . \quad . \quad . \quad . \quad . \quad (13)$$

and

$$V = (I_1 + I_B)Z_1 + (I_1 + I_B - I_L)Z_2 \quad . \quad . \quad (14)$$

where Z_1 and Z_2 have the values given in eqns. (7) and (8).

By subtraction it follows that

$$I_B(Z_1 + Z_2) = I_L Z_2$$

and

$$\frac{I_B}{I_L} = \frac{Z_2}{Z_1 + Z_2} = \frac{V_2}{V} \quad . \quad . \quad . \quad . \quad . \quad (15)$$

where V_2 is the voltage on the lower half of the regulator on no load.

This current ratio I_B/I_L is one of the quantities which can be deduced with a great number of other results from a full vector analysis as shown in Section 4.3, but this result itself follows much more simply from the equivalent T-network.

The current in the lower 'common' part of the winding, as in an auto-transformer, is equal in principle to the difference between the load component of input current I_B and the output load current I_L; but, as a result of the long air paths of the fluxes, the magnetizing current to be added is a good deal larger than in an auto-transformer of comparable size. Eqn. (15) is valid whatever the internal phase angles of the impedances Z_1 and Z_2; and it therefore means that the ratio of the *additional* input current to the output current, as load is increasingly imposed, should remain constant and equal to the ratio of the output voltage *on no load* to the constant line voltage. In addition to their ratio being numerically constant, the two quantities I_B and I_L should also be co-phasal, provided only that Z_1 and Z_2 are impedances of equal phase angle; and thus that V_2 and V, on no load, are also co-phasal. It was, in fact, found that this was so, for all positions of the moving coil, which confirms that Z_1 and Z_2 are at least of very nearly equal phase angle, even if this is less than 90°.

A large number of experiments ranging from no load to full load, and for power factors varying from unity to nearly zero, both lagging and leading, have verified that this constancy of ratio between additional input current I_B and output current I_L is accurately obtained in practice. This confirms that the imposition of considerable extra currents on all the windings does not sensibly affect the impedances of the windings; and that, therefore, the paths of the fluxes due to the additional currents are almost entirely air paths.

The regulator therefore acts, for any given setting of the moving coil, as a constant-ratio current transformer; and, as will later be shown, the effect of loading is to change the voltage ratio, in both magnitude and phase, from its no-load value, while leaving the current ratio constant. Both theory and practice equally confirm this general statement. Each position of the moving coil corresponds to one invariant current ratio, a whole series of such ratios being available by shifting the moving coil.

(4.3) On-Load Vector Analysis

In Section 4.1 and Fig. 1 the no-load vector equations have been obtained. If I_L is the load current which is then supposed to be drawn from the lower half of the winding, and if I_B and I_S are the corresponding *extra* currents in the input lead to the regulator and in the moving coil, respectively, a new circuit diagram may be drawn for the load condition as shown in Fig. 5.

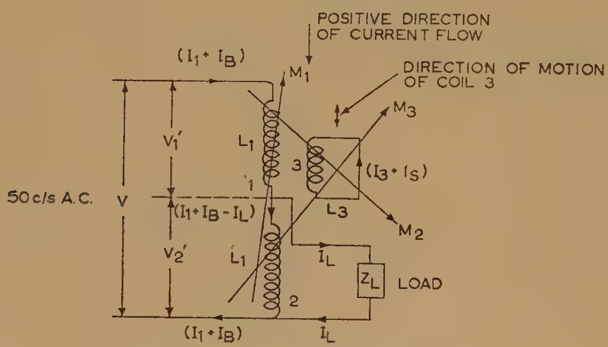


Fig. 5.—Circuit diagram on load.

From this the vector equations on load may be written as

$$V_1' = j[L_1(I_1 + I_B) - M_1(I_1 + I_B - I_L) + M_2(I_3 + I_S)]\omega \quad . \quad (16)$$

$$V_2' = j[L_1(I_1 + I_B - I_L) - M_1(I_1 + I_B) - M_3(I_3 + I_S)]\omega \quad . \quad (17)$$

$$0 = j[L_3(I_3 + I_S) + M_2(I_1 + I_B) - M_3(I_1 + I_B - I_L)]\omega \quad . \quad (18)$$

$$V_1' + V_2' = V \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

Subtracting from these equations the corresponding no-load equations for V and I_3, from Section 4.1, and performing a great deal of algebraic simplification, expressions are obtained for the load components of input and moving-coil currents (I_B and I_S, respectively) in terms of I_L, the output current. These are as follows:

$$\frac{I_B}{I_L} = \frac{(L_1 - M_1) + \dfrac{M_3}{L_3}(M_2 - M_3)}{2(L_1 - M_1) - \dfrac{(M_2 - M_3)^2}{L_3}} = \frac{Z_2}{Z_1 + Z_2} \quad . \quad (20)$$

and

$$\frac{I_S}{I_L} = -\frac{(L_1 - M_1)\dfrac{M_2 + M_3}{L_3}}{2(L_1 - M_1) - \dfrac{(M_2 - M_3)^2}{L_3}} \quad . \quad . \quad (21)$$

It will be observed that the expression for I_B/I_L is equal to the much simpler expression $Z_2/(Z_1 + Z_2)$ previously obtained in Section 4.2.

(4.4) Load Current in Moving Coil

The ratio I_S/I_L obtained in Section 4.3 can be reduced very nearly into a much simplified form as follows.

It has already been shown that the total no-load input impedance $(Z_1 + Z_2)$ is equal to

$$j\left[2(L_1 - M_1) - \frac{(M_2 - M_3)^2}{L_3}\right]\omega$$

where Z_1 and Z_2 are the effective no-load impedances of the two halves of the main winding and are, respectively,

$$Z_1 = j\left[(L_1 - M_1) - \frac{M_2}{L_3}(M_2 - M_3)\right]\omega$$

$$Z_2 = j\left[(L_1 - M_1) + \frac{M_3}{L_3}(M_2 - M_3)\right]\omega$$

Further, since $(Z_1 + Z_2)$ only alters by about 12% (the proportional variation of the magnetizing current) between its extreme values, and since $(M_2 - M_3)$ is zero when $(Z_1 + Z_2)$ has its maximum value, it follows that $2(L_1 - M_1)$ is much greater than $(M_2 - M_3)^2/L_3$ and that $(Z_1 + Z_2)$ may be nearly expressed as $j2(L_1 - M_1)\omega$.

We can thus simplify the ratio I_S/I_L, and we find that

$$\frac{I_S}{I_L} \simeq -\frac{M_2 + M_3}{2L_3}$$

which is nearly constant. If N_1 is the number of turns in coils 1 and 2, and N_3 is the number of turns in coil 3, it follows that

$$\frac{I_S}{I_L} \simeq -\frac{kN_1N_3 + kN_1N_3}{2kN_3^2} \simeq -\frac{N_1}{N_3}$$

where k may be taken as a single constant, since all the coils are wound on a common iron core. It should be noted that on load, as on no load, the current in the moving coil is inversely proportional to the number of turns in it. This confirms by analytical methods what was stated in Section 3.2; namely that the load current flowing round the lower half of the main winding can only be balanced by corresponding extra ampere-turns in the short-circuited coil.

(4.5) Output Voltage: Equivalent T-Network

We have already obtained the equations on load from which the output voltage may be deduced. These are

$$V_2' = j[L_1(I_1 + I_B - I_L) - M_1(I_1 + I_B) - M_3(I_3 + I_S)]\omega \quad . \quad (17)$$

and

$$(I_3 + I_S) = -\frac{(M_2 - M_3)(I_1 + I_B) + M_3 I_L}{L_3} \quad . \quad . \quad (18)$$

Substituting and simplifying, it follows that

$$V_2' = j\left\{(I_1 + I_B)\left[(L_1 - M_1) + \frac{M_3}{L_3}(M_2 - M_3)\right] - I_L\left(L_1 - \frac{M_3^2}{L_3}\right)\right\}\omega$$

Putting in the value for Z_2 already obtained, it follows that

$$V_2' = \left[(I_1 + I_B - I_L)Z_2 - jI_L\left(M_1 - \frac{M_2M_3}{L_3}\right)\omega\right]$$

$$= [(I_1 + I_B - I_L)Z_2 - I_L Z_3], \text{ say} \quad . \quad . \quad . \quad . \quad (22)$$

where

$$Z_3 = j\left(M_1 - \frac{M_2M_3}{L_3}\right)\omega \quad . \quad . \quad . \quad . \quad (23)$$

By inspection of the network shown in Fig. 4, it will now be clear that the value of Z_3, thus derived, is, in fact, the third impedance of the equivalent T-network; since the load voltage in the network shown will clearly be given by

$$V_2' = [(I_1 + I_B - I_L)Z_2 - I_L Z_3] \quad . \quad . \quad . \quad (24)$$

The first two impedances on open-circuit, Z_1 and Z_2, have already been deduced, and the network is thus fully specified.

(4.6) Predictions of Load Performance from No-Load and Short-Circuit Tests

Having reduced the regulator to an equivalent T-circuit, it is clearly possible to determine Z_1 and Z_2 from no-load tests, for any particular position of the moving coil, by simple measurements of the voltages V_1 and V_2 and of the current I_1, for a supply voltage V.

The supply voltage V is then removed and the supply terminals are short-circuited, and the effective regulator impedance Z_0, 'seen' from the output terminals, is measured. It follows from Fig. 4 that

$$Z_0 = Z_3 + \frac{Z_1 Z_2}{Z_1 + Z_2} \quad . \quad . \quad . \quad . \quad . \quad (25)$$

and since Z_1 and Z_2 are already known, Z_3 can at once be calculated. Z_3 commonly takes a negative value, and Z_0 is usually much smaller than Z_1 and Z_2, for most of the range of travel.

From these constants Z_1, Z_2, Z_3, and Z_0, used in eqns. (24) and (26), theoretical output-voltage curves for the regulator on full-load current were predicted for a full range of motion of the moving coil, both for a purely resistive load and for a (nearly) purely inductive load, and the theoretical curves of total input current ($I_1 + I_B$) were also calculated. Extensive practical tests showed exceptionally close agreement with theory, but detailed test results have been omitted for brevity. It is, however, of much interest that a piece of dynamo-electric equipment with substantial air-gaps should have proved itself exceptionally amenable to exact theoretical predictions of its performance. This would have been expected, but it is reassuring that such was found to be the case in practice.

The reverse impedance Z_0 already determined is, of course, the equivalent Thévenin network output impedance, and an equivalent load circuit can thus be drawn, to give the load voltage of the regulator, as in Fig. 6. From this circuit diagram,

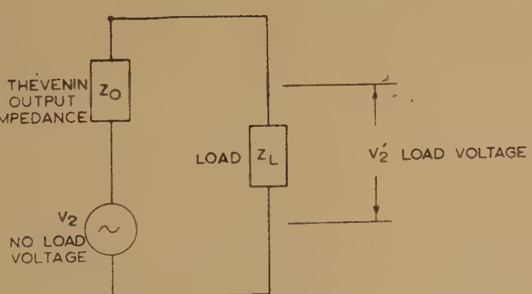


Fig. 6.—Calculation of regulator load voltage from Thévenin's theorem.

the load voltage V_2' can be written, in an alternative form to eqn. (24), as

$$V_2' = \frac{Z_L}{Z_L + Z_0}\,[\text{No-load voltage } V_2]$$

$$V_2' = V\frac{Z_2}{Z_1 + Z_2}\,\frac{1}{1 + \dfrac{Z_0}{Z_L}} \quad . \quad . \quad . \quad . \quad . \quad (26)$$

which is another equation which can conveniently be used to calculate the output voltage V_2' on load.

This equation enables the voltage variation with load, at unity power factor, to be displayed elegantly, in a graphical fashion, as in Fig. 7, which shows V_2' (and V_1') as vectors, for different loads, for a typical position of the moving coil.

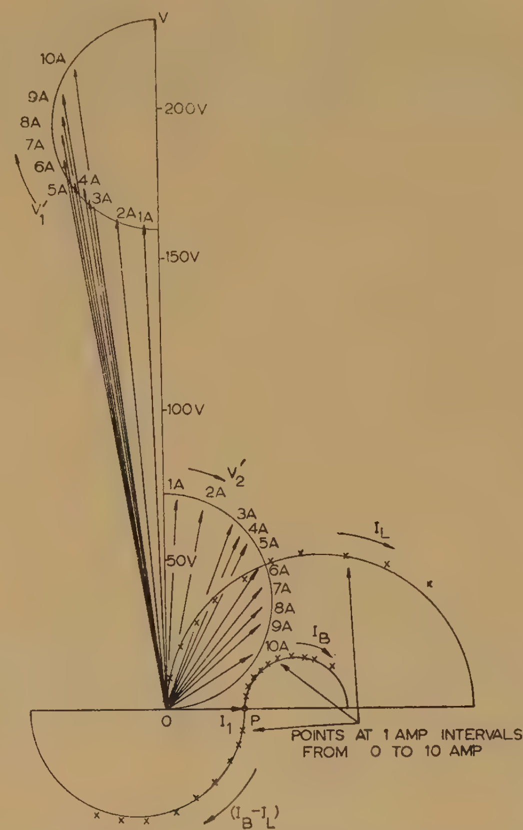


Fig. 7.—Vector diagram of regulator output voltages, for an intermediate moving-coil position, with varying resistive loads.

Input, 230 volts 50 c/s single phase.
Voltage circles predicted from

$$\frac{V_2'}{V} = \frac{Z_2}{Z_1 + Z_2}\,\frac{1}{1 + Z_0/Z_L}$$

Current circles predicted from

$$I_L = \frac{V_2}{Z_0}\,\frac{1}{1 + Z_L/Z_0}$$

$$I_B = \frac{V_2}{Z_0}\,\frac{Z_2}{Z_1 + Z_2}\,\frac{1}{1 + Z_L/Z_0}$$

$$I_B - I_L = \frac{V_2}{Z_0}\,\frac{-Z_1}{Z_1 + Z_2}\,\frac{1}{1 + Z_L/Z_0}$$

Experimental vectors are superimposed.
The coil travel is 33% from the bottom.
N.B.—The origin of the vectors I_B and $I_B - I_L$ is at the point P.

The basis of these diagrams, for loads at unity power factor only, is as follows:

We have, from Fig. 6,

$$V_2' = V_2\frac{1}{1 + \dfrac{Z_0}{Z_L}}$$

where Z_0 is a (nearly) pure reactance and Z_L is a pure resistance; and V_2' may thus be written

$$V_2' = V_2\frac{1}{1 + j\theta} \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

where $\theta = \dfrac{Z_0 \text{ (in ohms)}}{R_L \text{ (in ohms)}}$, and is a pure number.

As is well known, the locus of the current vectors representing the currents through a circuit consisting of a fixed reactance in series with an infinitely variable resistance is a semicircle. From Fig. 8, it is clear that

$$V_2' = I_L R_L = \frac{V_2 R_L}{R_L + jZ_0} = \frac{V_2}{1 + j\theta} \quad . \quad . \quad (28)$$

and thus the output voltage on load, V_2', with a load resistance R_L, is determined by describing a semicircle on the no-load

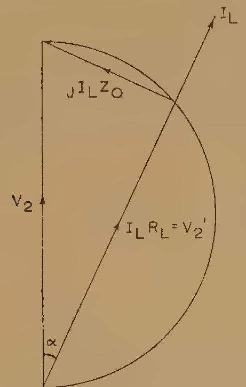


Fig. 8.—Circle diagram for purely resistive load.

voltage vector V_2 as diameter, and setting off a current vector I_L at an angle $\alpha = \arctan Z_0/R_L$. At once V_2' can be read off, and the value of the current I_L follows. Fig. 7 shows this quantity V_2' with experimentally determined vectors superimposed; and the values of V_1', the voltages on the upper 'unloaded' portion of the main winding, are also given, by difference, from a simple geometrical construction.

The vector loci of the currents I_L, I_B and $(I_B - I_L)$ are also semicircles, as shown below.

From eqn. (26) we have

$$V_2' = I_L Z_L = V_2 \frac{Z_L}{Z_L + Z_0}$$

and hence

$$I_L = \frac{V_2}{Z_0} \frac{1}{1 - j/\theta} \quad . \quad . \quad . \quad . \quad . \quad (29)$$

where α has the same meaning as before; and, from eqn. (15),

$$I_B = \frac{V_2}{Z_0} \frac{1}{1 - j/\theta} \frac{Z_2}{Z_1 + Z_2} \quad . \quad . \quad . \quad . \quad (30)$$

Subtracting eqn. (29) from eqn. (30) gives

$$I_B - I_L = \frac{V_2}{Z_0} \frac{-1}{1 - j/\theta} \frac{Z_1}{Z_1 + Z_2} \quad . \quad . \quad . \quad (31)$$

These eqns., (29), (30) and (31), are of similar vector form to eqn. (28), and it follows that I_L, I_B and $(I_B - I_L)$ can also be represented by semicircles.

It has already been shown that the semicircle for V_2' in Fig. 7 is defined by $V_2' = V_2/(1 + j\theta)$ [eqn. (28)]. Since $1/Z_0$ is a vector of $-90°$ phase rotation, and since the coefficient of j in eqns. (29), (30) and (31) is negative, it follows that the axes of the semicircles representing I_L, I_B and $(I_B - I_L)$ are turned 90° clockwise from the axis of the semicircle for V_2; and that the loci of I_L and I_B are in advance of their axes, instead of being behind them, as is the semicircle for V_2'. The minus sign in the numerator of eqn. (31) indicates that the axis of the semicircle for $(I_B - I_L)$ is advanced 180° from the axis of the semicircles for I_B and I_L; the locus still remaining in front of its axis.

Since these semicircles represent currents, their scale in relation to the voltage semicircles is arbitrary, but the diameter of the semicircle for I_L is V_2/Z_0; for I_B it is

$$\frac{V_2}{Z_0} \frac{Z_2}{Z_1 + Z_2}$$

and for $(I_B - I_L)$ is

$$\frac{V_2}{Z_0} \frac{Z_1}{Z_1 + Z_2}$$

It is clear from eqns. (30) and (31) that the load components of the currents flowing in the two halves of the main winding are in anti-phase, and that

$$I_B = -\frac{Z_2}{Z_1}(I_B - I_L) \quad . \quad . \quad . \quad . \quad . \quad (32)$$

These semicircles are shown in Fig. 7, the origin of the semicircles for I_B and $(I_B - I_L)$ being offset in the positive direction by the amount of the magnetizing current I_1. Experimental points are superimposed on the theoretical semicircles. Fig. 9

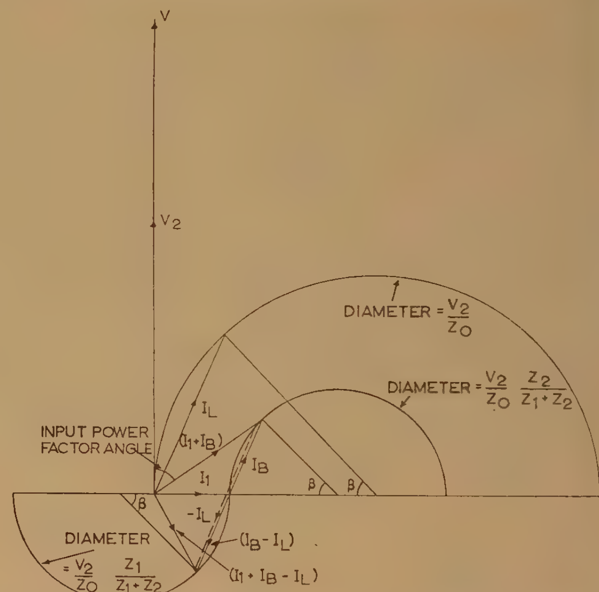


Fig. 9.—Typical current-vector diagram: theoretical construction.

is a typical theoretical current-vector diagram, showing the constructions which may be employed to determine theoretical values for comparison with practical results.

It is easy, by drawing parallel radii at equal angles β, to read off the values of all the components of current I_B, $(I_1 + I_B)$, $(I_B - I_L)$ and $(I_1 + I_B - I_L)$ corresponding to a given value of I_L. A very considerable number of such comparisons between theory and practice were made, with great success, but detailed results have been omitted from the paper for the sake of brevity.

Figs. 7 and 9 also show the input power-factor angle, and the angle between input and output voltages. It is clear that, in principle, only at zero power factor can the phase shift between input and output voltages, at all loads, be zero. Since the regulator has been shown to be nearly equivalent to a purely inductive network, it follows that only when a pure inductance (or capacitance) is connected to it will all the voltages in the network be co-phasal with the applied voltage. A series of tests on an inductive load confirmed that the output voltage was always co-phasal with the line voltage at zero power factor, and

nce again there was very close numerical coincidence between e theoretically predicted performance and the test results.

A rotating-core induction regulator, even on no load, has herent in its very principle a phase shift in voltage; though it is ue that this phase shift can be neutralized in a double-unit gulator. The moving-coil regulator has no such inherent o-load phase shift. On the other hand, the phase shift of a ormal transformer, even on load, is—so to speak—an accidental fect. It arises from the fact that some of the flux leaks from its eal magnetic path, and though this leakage flux has substantial actical consequences, it is essentially a second-order effect.

The moving-coil regulator seems to stand logically between iese two positions. There is no inherent phase shift in no-load oltage, but there is an inherent voltage phase shift on load hich cannot be regarded as a second-order effect. In principle, s shown in Section 4.1, the moving-coil regulator is an inductive otential divider, and the phase shift on load of any inductive otential divider, which must occur when supplying any load xcept a load at zero power factor, cannot truly be regarded as a econd-order effect.

The prototype regulator is commonly interwound and inter-onnected with other transformer-coupled windings[3] so that the verall output voltage may have only a small phase shift, because ie regulator element itself contributes either a small voltage omponent at a big angle of shift or a larger voltage component t a smaller angle of shift.

Since the rotating-core type of induction regulator has an nherent phase shift even on no load (unless this shift is cancelled y a double-unit arrangement) the moving-coil regulator, as pplied, is superior overall in regard to the phase shift caused; ut it is not quite true that the phase shift is negligible.

(4.7) Ratio of Output Volt-Amperes to Input (Load) Volt-Amperes: Locus Diagram

In eqn. (26) we have the relation between input and output oltages as

$$V_2' = V\frac{Z_2}{Z_1 + Z_2}\frac{1}{1 + Z_0/Z_L}$$

In eqn. (15) we have the relation between input (load) current nd output current as

$$\frac{I_B}{I_L} = \frac{Z_2}{Z_1 + Z_2}$$

Combining these, we obtain the results

$$V_2' I_L = VI_B\frac{1}{1 + Z_0/Z_L}$$

or

$$\frac{\text{Output volt-amperes}}{\text{Input (load) volt-amperes}} = \frac{1}{1 + Z_0/Z_L} = \frac{V_2'}{V_2} \quad . \quad (33)$$

In a normal auto-transformer this vector quotient, ignoring second-order effects, is unity, the input and output volt-ampere products being equal and co-phasal. In the regulator the vector quotient is never unity, even in principle, except on no load ($Z_L \to \infty$); and is never equal to a pure number except when Z_L and Z_0 are vectors of the same type, i.e. when Z_L is a pure reactance. When Z_L is a pure resistance the locus diagram for the volt-ampere ratio is a semicircle, for the same reasons as explained in relation to eqns. (27) and (28) and Fig. 8.

The important conclusion is thus reached that, even ignoring the larger magnetizing current I_1 and the leakage flux, a volt-ampere balance can, in general, not be looked for in this regulator. The relationship between volt-ampere products is summarized by the general vector diagram of Fig. 10, on which experimental

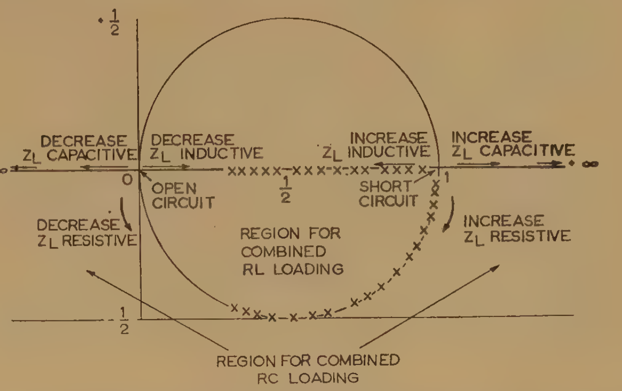


Fig. 10.—Polar diagram (output/input volt-amperes) for loads from zero to short-circuit, resistive and inductive.

Theoretical curve calculated from Z_1, Z_2 and Z_3, with experimental points superimposed.

points have been superimposed. This is another important respect in which the performance of the regulator must be differentiated from that of a normal power transformer, apart from the larger values of magnetizing current and leakage reactance in a regulator, as compared with a transformer of similar rating.

(4.8) Forces on the Moving Coil

It is impossible by pure theory accurately to predict the net force on the moving coil, because considerations of the rate of change of inductance, in space, of a complicated geometrical form defy exact calculation, though reasonable estimates can be made. Certain firm conclusions, can, however, be reached about the resultant force on the moving coil in the central position, when the regulator is on load. This force will not be zero, though it will be very much less than the force corresponding to full currents in all the windings.

The current in the main winding can be regarded (see Fig. 5) as being composed of a current $(I_1 + I_B)$ flowing downwards through the entire winding, with a further current I_L, flowing in an upward direction, superimposed on the lower half of the winding only. When the moving coil is situated at the middle of its travel, the current $(I_1 + I_B)$ flowing in each half of the main winding will exert a net force on the moving coil, when it carries a current I_s, which can be written $2k(I_1 + I_B)I_s$, where k is an arbitrary constant. (It should be noted that the forces due to the two halves of the main winding carrying the same current are additive when the two coils are connected in opposite senses: if the coils were connected in the same sense the forces would be opposed.) On the other hand, the current $-I_L$ flowing in one half of the main winding will cause another force opposed to the first force, and which can be written as $-kI_L I_s$. Taking the algebraic sum, the resultant force is

$$2k(I_1 + I_B)I_s - kI_L I_s$$

But in the central position $2I_B = I_L$, and the total resultant force is therefore $2kI_1 I_s$.

It thus follows that the resultant force on the moving coil at the centre of its travel, when the regulator is on load, is equal to the force which would occur if the main winding were carrying the magnetizing current I_1 only and the moving coil were carrying a current I_s. These currents, I_1 and I_s, are nearly in quadrature on unity-power-factor load, but are co-phasal on loads of low power factor. It is thus clear that while the resultant force on the moving coil in the central position, on load, is not quite zero—because I_1 is rather larger relatively than for an ordinary

transformer—it is very much reduced by counter-connection of the coils and is industrially of no importance. It is equally clear that in any other position of the moving coil there will be substantial cancellation of component forces, and that the resultant force will always be moderate.

(5) ACKNOWLEDGMENTS

The authors acknowledge with very grateful thanks their interesting discussions with Mr. E. T. Norris, who originally developed the regulator, and with Mr. A. J. Glover, both of Ferranti Ltd., and also the generosity of the Company, who presented a regulator to the University of Bristol. They also wish to say that the possibility of representing the regulator by the circuit of Fig. 4 was first pointed out in discussion with Mr. A. R. Billings, Lecturer in the University of Bristol. This work was part of that done by one of the authors while holding, in the University of Bristol, the Silvanus Thompson Scholarship of The Institution of Electrical Engineers.

(6) REFERENCES

(1) NORRIS, E. T.: 'The Moving-Coil Voltage Regulator', *Journal I.E.E.*, 1938, **83**, p. 1.

(2) NORRIS, E. T.: 'The Moving Coil Voltage Regulator' (Ferranti, Ltd., 1937).

(3) NORRIS, E. T.: 'The Moving Coil Regulated Transformer', *Beama Journal*, 1948, **55**, p. 306.

DISCUSSION ON 'A SHORT MODERN REVIEW OF FUNDAMENTAL ELECTROMAGNETIC THEORY'

The paper (No. 1595), by MR. P. HAMMOND, *was published separately in December, 1953, and was republished, together with the London discussion and a number of written contributions, in July, 1954, in Vol. 101, Part 1, of the* PROCEEDINGS (p. 147). *A contribution by* MR. C. HARGREAVES *appeared in February, 1956, in Vol. 103 A (p. 38), after which it was considered that the correspondence on this subject should be closed. However further contributions have been received—from* PROFESSOR E. G. CULLWICK, MR. HARGREAVES *and* MR. W. F. LOVERING*—and these have been carefully considered by the author in preparing this, his final reply to the discussion.*

Mr. P. Hammond (*in reply*): Mr. Hargreaves continues the discussion of the expanding rectangular circuit.* He suggests an arrangement by which the circuit would surround an iron core, the contention being that this would increase the $\frac{\partial \boldsymbol{B}}{\partial t}$ and $\frac{d\phi}{dt}$ effects but would leave the $\boldsymbol{u} \times \boldsymbol{B}$ effect unaltered. Eqn. (22) would then give a different value for the e.m.f. from that given by eqn. (14).

Mr. Lovering takes up Mr. Hargreaves's problem. His conclusion is that eqns. (22) and (14) are always consistent, but he deprecates the division of the e.m.f. into a flux-cutting and a flux-changing part.

Prof. Cullwick questions the derivation of eqn. (22) from eqn. (14) for cases in which the circuit is not rigid. He prefers to derive the e.m.f. from the line integral of the Lorentz force $\boldsymbol{F} = \boldsymbol{\mathscr{E}} + \boldsymbol{u} \times \boldsymbol{B}$. He feels that problems containing a rotating disc or cylinder should be treated as a separate class, because the circuit in such cases contains no definite linear boundary.

All these contributions deserve a much more detailed reply than can be given in the space at my disposal.

The essence of Mr. Hargreaves's objection to the treatment of Faraday's law in my paper seems to lie in the transition from the equation

$$\oint \boldsymbol{\mathscr{E}} \,.\, d\boldsymbol{l} = -\frac{dt}{d}\iint \boldsymbol{B} \,.\, d\boldsymbol{a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

to

$$\oint \boldsymbol{\mathscr{E}} \,.\, d\boldsymbol{l} = -\iint\left[\frac{\partial \boldsymbol{B}}{\partial t} - \operatorname{curl}(\boldsymbol{u} \times \boldsymbol{B})\right] . \, d\boldsymbol{a} \quad . \quad . \quad (22)$$

Mr. Hargreaves is prepared to accept eqn. (14) but not eqn. (22). As pointed out in the paper, the step from eqn. (14) to eqn. (22) is a mathematical one and involves no new physical facts except the universally accepted statement that $\operatorname{div} \boldsymbol{B} = 0$ [eqn. (21)], i.e. that we have no experience of free magnetic poles. I do not share Prof. Cullwick's doubts as to the validity of Abraham and Becker's derivation of eqn. (22). Their treatment seems to be quite general, because the velocity $\boldsymbol{u}$ is given for each element of the circuit, which can therefore be deformed in any way whatsoever. In any case Prof. Cullwick arrives at the same results, although he prefers a different derivation.

The presence of an iron core would modify the magnetic field and attention would have to be paid to the induced surface polarity of the core, but Faraday's law as stated in eqn. (22) would continue to be applicable. Here at least Mr. Lovering and Prof. Cullwick agree with me. It cannot be pointed out too strongly that eqn. (22) is a mathematical statement which demands that the line integration of the left-hand side should exactly surround the area integration of the right-hand side. Current can only flow in conductors of finite cross-section. If, therefore, the line integration is carried out round a circuit that lies within the conductor material, it is essential to include the flux density within that material in the calculation. It is true that the additional area included in the integration may be small, but the flux density changes very rapidly in this small area and the contribution to the e.m.f. may be dominant. Since different paths of integration can be chosen which will give the same value for the line integral, Mr. Lovering is quite correct in pointing out that the flux cutting and threading terms are not unique. Nevertheless, in very many cases it is exceedingly helpful to separate the two effects.

Prof. Cullwick has consistently urged that the student's attention should be directed to the forces acting on electric charges. It can be seen from my paper that I entirely agree. But I am not convinced that it is wise in teaching to start with the Lorentz force and derive Faraday's law of induction from it. If the time comes when particle accelerators are more common in the laboratory than induction motors, I may change my mind. The sequence of instruction is clearly not very important. I do not feel that the homopolar generator is in a class by itself, because here again one is free to choose any convenient circuit for the integration of eqn. (22).

It is good to know that teachers will continue to debate these matters. The many contributions to this discussion have shown that fundamental theory is a very live issue, and the interest of the teacher cannot fail to stimulate interest in the student.

* Mr. Hargreaves wishes to point out that the third term in his eqn. (*a*) (see 103 A, p. 38) should read

$$\frac{\sqrt{(L^2 + s^2)}}{L}$$

1.313.334

Paper No. 2231 U
Feb. 1957

A STATOR-FED HALF-SPEED SYNCHRONOUS MOTOR

By R. L. RUSSELL, M.Sc., Associate Member, and K. H. NORSWORTHY, B.Sc., Graduate.

(*The paper was first received* 12*th July, and in revised form* 12*th September*, 1956.)

SUMMARY

It is well known that an induction motor with an asymmetrically onnected secondary circuit will run at a fractional slip rather greater an 0·5 but that the asynchronous performance is not wholly satisfactory. The defects arise chiefly, though not entirely, from a rotor eld component which rotates with a small angular velocity $(1 - 2s)\omega$, nd is responsible for reflecting undesirable low-frequency currents to the primary supply system. These disadvantages are avoided by uperimposing a stationary magnetic field which fixes the $(1 - 2s)\omega$ eld in space and thus compels the rotor to run at $s = 0{\cdot}5$, i.e. at xactly half speed. Further, the power factor can be controlled by ltering the d.c. excitation in the usual way, and good efficiencies can e achieved. Test results are quoted for three different types of rotor nd compared with a first-order theory which provides suggestions for nproved rotor design and further developments.

LIST OF PRINCIPAL SYMBOLS

ω = Angular frequency.
s = Fractional slip.
I_{DC} = Direct current.
$\boldsymbol{I}_{DC0}$, I_{DC0} and i_{DC0} = Vector, r.m.s. and instantaneous values, respectively, of the alternating current per phase corresponding to I_{DC}, as found in the zero a.c. test.
$\boldsymbol{V}$, V and v = Vector, r.m.s. and instantaneous values, respectively, of alternating voltage per phase.
$\boldsymbol{Z}$ = Complex stator impedance per phase in zero d.c. test.
ϕ = Argument of $\boldsymbol{Z}$.
$\boldsymbol{S}_D$ and $\boldsymbol{S}_Q$ = Complex direct- and quadrature-axis reluctances, respectively.
Φ_D and Φ_Q = Direct- and quadrature-axis rotor fluxes, respectively.
$\boldsymbol{Z}_D$ and $\boldsymbol{Z}_Q$ = Direct- and quadrature-axis impedances, respectively, corresponding to Φ_D and Φ_Q, referred to the stator.
θ_0 = Angular position of the rotor with respect to the reference axis at $t = 0$.
λ = Conversion ratio, modulus of $\dfrac{\boldsymbol{Z}_D - \boldsymbol{Z}_Q}{\boldsymbol{Z}}$.
α = Non-dimensional parameter, $\dfrac{I_{AC0}}{I_{DC0}}$.
T = Torque, N-m.

For ease of comparison, graphical results for the salient rotor S), the cylindrical rotor with concentrated winding (CW), and he salient rotor with single-phase winding (SW) will be denoted, espectively, by squares, circles and triangles.

(1) INTRODUCTION

The present account is devoted to a particular application of he differential principle discussed by one of the authors in an earlier paper.[1] Briefly, when a balanced 3-phase supply is connected to an orthodox 3-phase star-connected winding, a uniform rotating field is produced in the usual way. When, however, the neutral connections are separated and the ends thus freed are connected to a second 3-phase system, with the same magnitude as the first but with reversed phase sequence, the resultant field varies both in space and time. For example, in a 2-pole machine the resultant field varies sinusoidally at half the sum of the angular frequencies of the supply systems, $(\omega_2 + \omega_1)/2$, about an axis which rotates with an angular velocity equal to half their difference, $(\omega_2 - \omega_2)/2$.

This result can be employed in a number of ways. In one of them a machine with a salient-pole rotor is used. The rotor tends to align itself with the resultant field axis and therefore rotates with angular velocity $(\omega_2 - \omega_1)/2$, thus behaving as a differential. It is a particular case of differential operation, when the frequency of one supply system is zero, which is discussed in the paper.

When the angular frequency of one system is ω, and of the other is zero, the angular velocity of the rotor, from the results quoted above, is $\omega/2$ and the machine therefore behaves as a half-speed synchronous motor. The correct electrical condition corresponding to zero frequency is not, of course, that the second system should be removed completely but that it should be energized to produce an m.m.f. which is stationary in space. This is achieved by feeding direct current of appropriate magnitude and sign to the windings. This is sometimes referred to as a 'frozen' 3-phase supply, and, clearly, any values of direct current corresponding to the instantaneous phase values could be used, but the simplest circuit arrangement is that in which the direct current is passed through one phase winding in series with the remaining two connected in parallel, as shown in Fig. 1. By adjusting the direct current it is possible to obtain better values of power factor and efficiency than can otherwise be achieved under exact or approximate half-speed operation.

Before pursuing the argument in detail it is relevant to observe at this stage that near half-speed effects in induction motors with unsymmetrical secondaries have been known for some considerable time, and have been well catalogued since they were first described some 60 years ago. They have not, however, found much use in practice, and, in a recent paper[2] which has revived interest in the topic, this is attributed to defects arising from magnetic saturation and the generation of low-frequency currents in the supply system, to which might be added the disadvantage of a low power factor. The first of these can be avoided, but the second is inherent in the performance of the induction motor with an unsymmetrical rotor, as it is essentially an asynchronous motor, in which slip varies with load, running at something less than half speed. These low-frequency currents at a frequency $(1 - 2s)f$, where f corresponds to synchronism, produce noise and vibration in the machine and are not desirable in the supply system. Their effects are avoided entirely when the machine is made to run at exactly half speed. Schenfer,[3] who was well aware of the effect produced by employing a single-phase connection on the rotor of an ordinary induction motor, achieved exactly half speed, and thus avoided the defects referred to, by providing an additional stator winding carrying a

Written contributions on papers published without being read at meetings are nvited for consideration with a view to publication.
The authors are in the Department of Electrical Engineering, University of Bristol.

direct current. Very briefly, the slowly rotating field at a frequency $(1 - 2s)f$ which would ordinarily be present is fixed in space when the direct-current field is superimposed, and, as a consequence, the rotor is constrained to run at $s = 0 \cdot 5$, i.e. at exactly half speed. There were disadvantages attached to the circuits suggested by Schenfer, and his verbal explanation was referred, somewhat inadequately, to the cascade induction motor, but there is no doubt that his proposals based on semi-intuitive reasoning were similar in principle, though different in origin, to those advanced in the present paper.

Both the papers referred to above[2,3] and others of a similar nature have in common an asymmetrically connected rotor circuit—asymmetrical connections, that is to say, on a symmetrical cylindrical rotor. In the authors' view the essential feature is lack of symmetry, however secured, and an equivalent effect is obtained by using a salient-pole rotor. Ideally, the rotor should have zero reluctance in one direction, and at right angles to this direction the reluctance should be infinite. In practice, the ratio between the direct-axis and quadrature-axis reluctance should be as large as possible.

A short-circuited single-phase winding on a cylindrical rotor reduces the effective reluctance along the coil axis and leaves it substantially unchanged in a direction at right angles to it. The salient-pole rotor, on the other hand, relies simply on the removal of magnetic material to produce the desired effect, and, though the quadrature flux will be reduced as compared with the direct axis flux, it will not be zero. The quadrature flux can be still further reduced, or, what is the same thing, the effective quadrature reluctance can be increased, by putting a short-circuited single-phase winding on the quadrature axis and thus combining the merits of both the methods just mentioned.

For purposes of direct comparison of results the machine as used in Fig. 1 was tested with three rotors in turn: (*a*) a cylindrical rotor with a short-circuited single-phase winding, (*b*) a salient-pole rotor, and (*c*) a salient rotor with short-circuited winding on the quadrature axis. For ease of reference these will be denoted henceforth as rotor CW, rotor S and rotor SW, respectively.

As in each case either the applied voltage or the d.c. excitation can be varied, most tests yield a family of curves, and in a comprehensive investigation a large number of graphs is obtained. Many of these have had to be omitted, and in the results which follow, one or two curves have been selected to represent a complete set.

(2) THEORY

When the rotor is running at exactly half synchronous speed, $\omega/2$, the m.m.f. produced by the 3-phase currents in the stator winding of the machine connected as in Fig. 1 will rotate with angular velocity $\omega/2$ with respect to the rotor. The rotor in turn is moving with angular velocity $\omega/2$ with respect to the direct-current m.m.f. The direct-axis rotor flux will thus

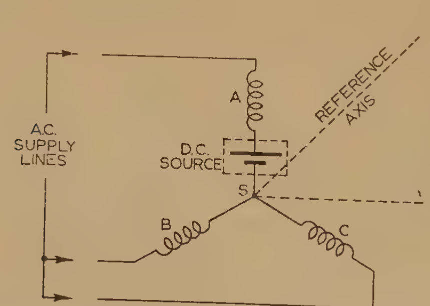


Fig. 1.—Diagram of the stator circuit connections for the half-speed synchronous motor.

be the resultant of two components, each of angular frequen $\omega/2$, one arising from the a.c. system and the other from the d. system. The phase of the resultant rotor flux clearly depends c the position of the rotor relative to the separate m.m.f.'s and w change as the rotor is retarded, as it will be, for example, on loa

The direct-axis rotor flux, which varies sinusoidally wi angular frequency $\omega/2$, can be resolved into two equal com ponents rotating in opposite directions with uniform angul velocity $\omega/2$ with respect to the rotor. As the rotor itself ha an angular velocity $\omega/2$, one of these components is stationa in space and does not therefore induce e.m.f.'s in the stat windings. The other component rotates with angular velocity ω and the e.m.f.'s which it induces in the stator are therefore supply frequency and are balanced. Precisely similar statemen apply to the quadrature-axis flux.

By controlling the back-e.m.f., the direct current provides means of modifying the machine characteristics—torque, effic ency and power factor—in a manner which is not obvious fro a casual inspection of the circuit arrangements.

The explanations advanced in the preceding paragraph, whe cast in analytical form as in Section 9.4, show that, with th assumptions implicit in the argument adopted, the performanc of the machine can be represented by the vector diagram o Fig. 2. Taking the voltage vector as a direction of reference, th

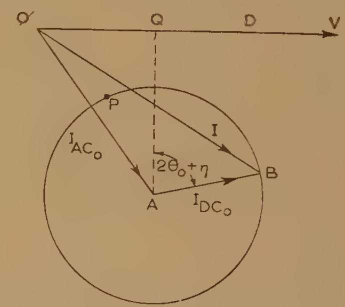


Fig. 2.—Vector locus for the half-speed synchronous operation.

centre of the circle is at a fixed distance I_{AC0} from the origin in a direction inclined at an angle ϕ to it. This distance is numericall equal to the stator-coil current I_{AC0} as determined in a test in which the 3-phase supply only is connected to the windings and the rotor is driven at a half synchronous speed, and ϕ is the phas angle between the current and the corresponding phase voltag under these conditions.

The relation between current and voltage in this zero d.c test is

$$\left.\begin{aligned} i_{AC0} &= \sqrt{2}\frac{V}{Z}\cos(\omega t - \phi) \\ \text{or} \qquad I_{AC0} &= \frac{V}{Z} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (1)$$

where Z is the impedance defined by the quotient of voltage and current, and ϕ is found from a measurement of power. The impedance Z can be written:

$$Z = Z_S + Z_D + Z_Q \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where Z_S is the combined stator resistance and leakage reactance, and Z_D and Z_Q are effective stator impedances representing, in magnitude and phase, the stator-induced e.m.f.'s arising from the rotor fluxes along the direct and quadrature axes, respectively.

The radius of the circle is eqnal to the value of the alternating stator-coil current I_{DC0} when the a.c. supply is reduced to zero and the rotor is driven at a half synchronous speed in the field

roduced by the direct current only. Then, as shown in ection 9.3,

$$\left.\begin{aligned} i_{DC0} &= -\left|\frac{Z_D - Z_Q}{Z}\right| I_{DC}\sin(\omega t - 2\theta_0 - \eta) \\ I_{DC0} &= \frac{\lambda}{\sqrt{2}} I_{DC} \text{ and } \lambda = \left|\frac{Z_D - Z_Q}{Z}\right| \end{aligned}\right\} \quad . \quad (3)$$

here I_{DC} is the d.c. excitation, λ is the ratio between the magni-ıde of d.c. excitation and corresponding peak alternating current, is the angle by which the direct axis of the rotor lags behind ıe reference axis at $t = 0$, and, largely for analytical convenience, ıe reference axis is taken as itself lagging $\pi/4$ on the axis of the esultant d.c. field. The angle θ_0, though not exactly equal to ıe load angle, is closely related to it since η will usually be small. s the mechanical load increases, for example, the rotor is etarded and θ_0 therefore increases. For different values of ıechanical load, both positive and negative, the vector OB will ıerefore occupy different positions in the circle.

The vector diagram, or strictly the vector locus, is in principle pecified from information provided in two separate tests, one which the a.c. supply only is employed and the other in which ıe d.c. supply only is used.

The zero d.c. test is not unlike an open-circuit test in which the ower supplied corresponds to the magnetizing requirements of ıe machine. The term $\dfrac{Z_D - Z_Q}{Z}$ relates direct and alternating ırrents in the zero a.c. test, in which the machine behaves as an ıductor alternator, and λ could therefore be called a conversion ıctor. Alternatively, λ could be described as a 'factor of ıliency', but, whatever term is used, it plays a most important art in determining the half-speed performance. As Z_Q pproaches Z_D, for example, this factor decreases until in the mit it is zero and the d.c. excitation is ineffective, as would be xpected for a symmetrically-wound cylindrical rotor for which Z_D and Z_Q would be equal.

(3) PRACTICAL RESULTS

(3.1) Apparatus and Tests

For test purposes, a standard 2-pole 5 h.p. 440-volt delta-conected 3-phase induction motor of ordinary commercial quality ʼas used. Except that both ends of all three coils were available, ıe stator winding was of the ordinary distributed kind contained 24 straight, partially-closed slots, and required no alteration. he frame was mounted on trunnion bearings and connected irectly to a simple torque-measuring rig. Two identical cylinrical rotors were assembled from circular pre-punched stampıgs, and, in one of them, deep slots of angular width 90° were ıilled to produce the salient poles required. The shaft was ırned during machining to give a skew on the poles of one tator slot pitch in order to avoid cogging effects which earlier ests had shown would otherwise be present.

This method of construction was adopted for convenience and conomy, and, as a result, each salient pole contained four closed lots which were not essential and would be omitted in a specially esigned salient rotor.

Both rotors were fitted with identical single-phase windings, onsisting of four parallel coils, each of nine turns of 16s.w.g., ontained in eight slots. The winding on the cylindrical rotor ʼas short-circuited: that on the salient-pole rotor was shortircuited or open-circuited, as required. Quite often, when comaring one type of construction with another, there are other ifferences, in addition to the particular ones in question, to onfuse the issue. By using a common stator, similar magnetic tamping, identical rotor coils, etc., such differences as are observed in the present tests can be attributed more directly to changes in rotor design.

Clearly, to avoid magnetic saturation, when two voltage systems are applied simultaneously to the stator windings of the machine, as in the present application, each must have a value lower than that which would be permissible if only one of them were to be employed. An a.c. line voltage of 260 volts (r.m.s.) was therefore taken as standard for the star-connected stator windings.

As the machine described is essentially a synchronous device, a significant parameter, especially by analogy with the orthodox synchronous motor, is the load angle, which was determined by using a stroboflash and an arbitrary circular scale on the rotor shaft.

Obvious tests are to find the variation of torque, efficiency and power factor with load angle, for different values of the d.c. excitation, and to compare the results with those deduced from the vector locus.

The presence of direct current of any appreciable magnitude in the secondary winding of the supply transformer is clearly undesirable and provides a practical restriction to the method. Further, it would be an advantage if a separate d.c. source could be dispensed with. Tests were therefore performed with the battery of Fig. 1 replaced by a single-phase rectifier.

(3.2) Machine Parameters

A number of parameters are defined and used in Section 9, but all that is required in order to construct the vector locus is, in principle, a knowledge of Z and λ. These are determined from separate zero a.c. and d.c. tests as explained in Sections 9.3 and 9.4. Corresponding to the linear part of the magnetization curve, the values show only small variations except over the upper range of d.c. and a.c. excitation. The average values obtained on test are given in Table 1.

Table 1

AVERAGE TEST VALUES OF Z AND λ

Rotor	Z	ϕ	Zero volts d.c., 150 volts a.c.		$\left\lvert\frac{Z_D - Z_Q}{Z}\right\rvert = \lambda$	Light-load test	
			Current	Power loss		Current	Power
	ohms	degrees	amp	watts		amp	watts
S	227	82	0·66	40	0·60	0·42	43
SW	210	81	0·71	52	0·91	0·30	54
CW	276	84	0·54	27	0·85	0·48	74

(3.3) Light-Load Test

Referring to Fig. 2, it is clear that when I_{AC0} and I_{DC0} are nearly equal there will be some values of load angle for which the resultant alternating current will be small. It follows that errors in the initial measurements of I_{AC0} and I_{DC0} may well lead to large discrepancies between theory and practice in this region. As is usual where the small difference of relatively large quantities is concerned, attempts are made to measure the difference directly. This is most simply done by finding the alternating current and power supplied in a separate light-load test. This determines the position of one point, P say, on the circle whose radius is found in the zero a.c. test. The centre of the circle is chosen to correspond to the measured power in the zero d.c. test. This is done by constructing a constant-power line perpendicular to the voltage vector through a point Q, where OQ is proportional to the quotient of the measured power and the applied voltage. Given that the centre lies on this line, it is a

simple geometrical exercise to find its position when one point on the circumference, P, is fixed and the radius is known. When, as in the present tests, I_{AC0} and I_{DC0} do not differ by much, the vector locus derived in this manner can be used with the assurance that there is no marked deterioration in accuracy for critical values near the origin.

(3.4) Torque and Load Angle

It is shown in Section 9.6 that the torque is given approximately by

$$T = \frac{6VI_{DC0}}{\omega}\sin 2\theta_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The theoretical torque/displacement curves in the first and third quadrants should ideally be similar, whereas the experimental results in Fig. 3, which, for simplicity, shows only one of

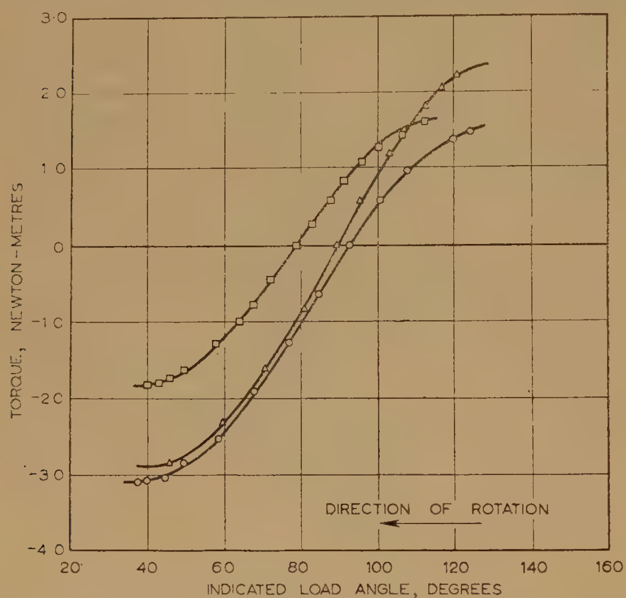


Fig. 3.—Half-speed synchronous performance of the two-pole machine with asymmetrical rotors.
$V = 150$ volts, $I_{DC} = 1\cdot5$ amp.

a family of curves for each rotor, are all of the sin 2θ form but are displaced negatively with respect to the θ axis. A simple overall displacement which leaves the peak-to-peak values of torque, as given by eqn. (4), unchanged is easily shown to correspond to constant losses. There is no reason to suppose in advance that the assumption of constant losses is any more than an approximation to the conditions which actually exist, yet the observed peak-to-peak values of torque do not differ from those predicted from eqn. (4) by more than 2%, except for the rotor SW for which the error is about 4%. Indeed, the departure of the unadjusted theoretical curve from the observed one is remarkably uniform, as shown by Fig. 4. The displacement for the machine with the salient-pole rotor is, not unreasonably, very small, since the impedances Z_S, Z_D and Z_Q are largely inductive, corresponding to a power loss which is relatively small [see Fig. 4, curves B(S) and B″(S)]. The short-circuited windings on rotors CW and SW, whatever their other effects, introduce an additional power loss and a greater displacement of the ideal curve in each case.

The adjusted theoretical curve obtained by allowing for light-load losses, as discussed in Sections 3.3 and 9.6, is shown in Fig. 4 for rotor CW, the effect being to produce better correspondence with the practical curve. For rotor S, for which the

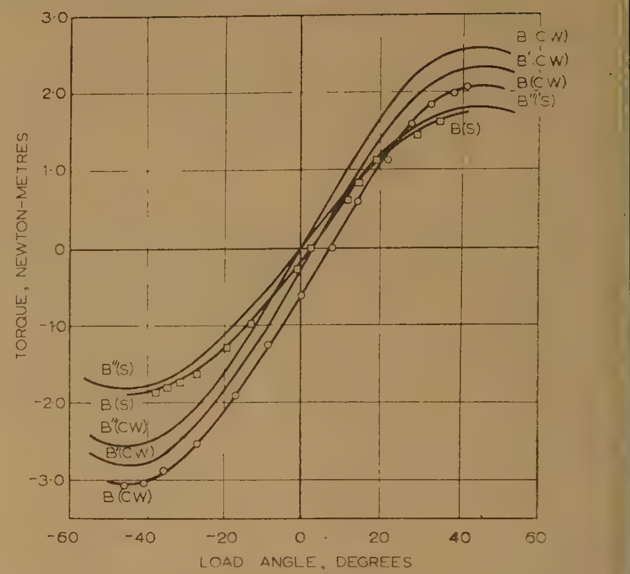


Fig. 4.—Comparison of theoretical and practical torques.
$V = 150$ volts, $I_{DC} = 1\cdot5$ amp.
Symbols S and CW define the rotor used: B, B′ and B″ refer to practical, adjust theoretical and unadjusted theoretical curves, respectively. Similar results are obtain for rotor SW.

fit in any event is good, the adjustment is negligible, and fo rotor SW there is no appreciable change; to avoid confusio the latter curves have therefore been omitted.

By choosing a rotor for which $Z_Q < Z_D$, it is possible to secu a larger value of I_{DC0} for the same d.c. excitation. There is no necessarily an increased motoring torque, and hence a large output, as a simple interpretation of eqn. (4) might suggest. A increase in peak-to-peak torque may be more than offset by th negative displacement when machine losses are taken into accoun The quadrature impedance of the salient rotor, for example, reduced by employing short-circuited turns on the quadratu axis, and the conversion factor λ is increased from 0·6 to 0·9 (se Table 1). The effect of so doing is diminished by the increase ohmic losses, as indicated in the zero d.c. test, from 40 to 52 watt

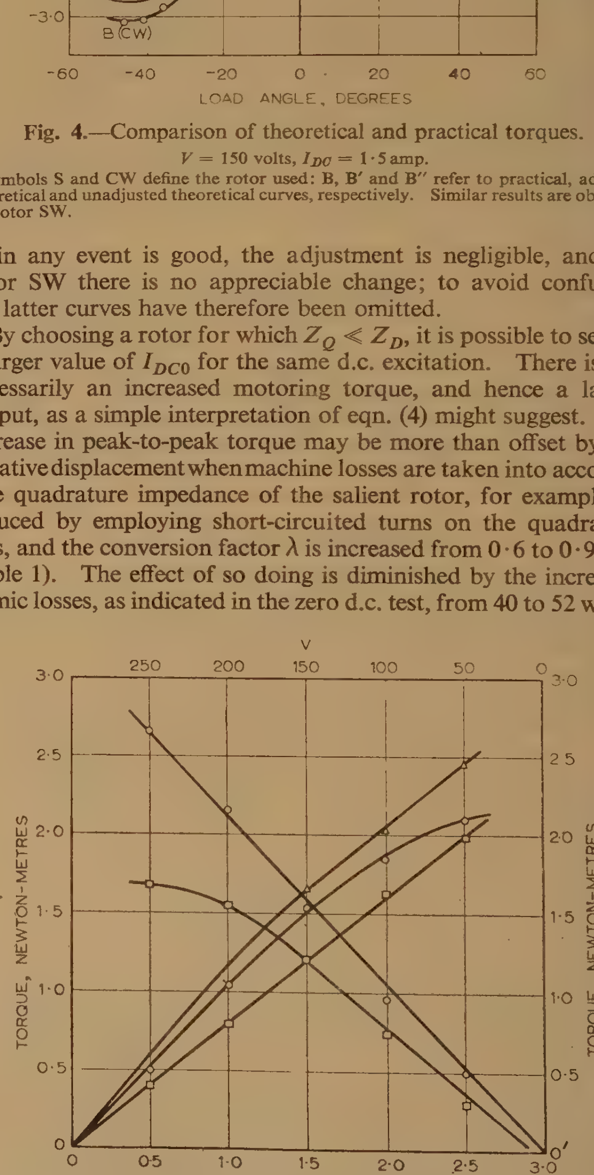
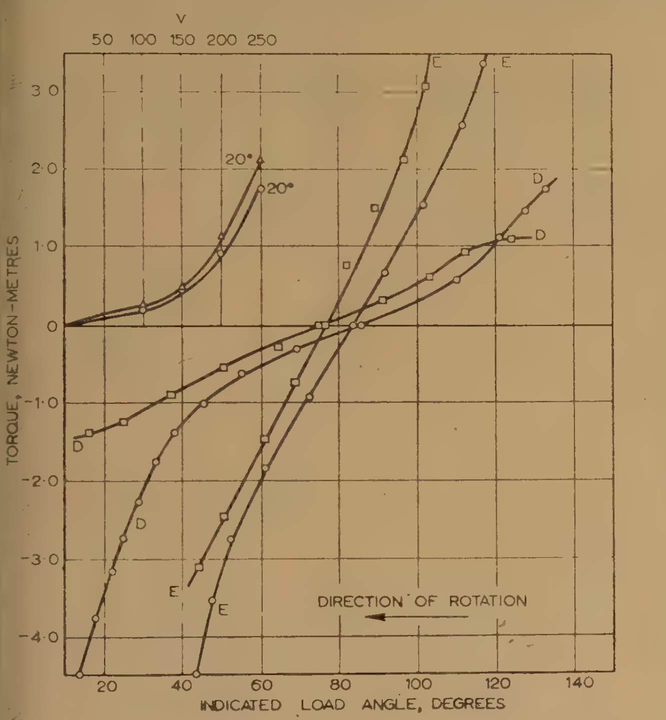


Fig. 5.—Variation of torque with applied voltage V and excitatio current I_{DC}.
Current curves have their origin at O; voltage curves have their origin at O′. All curves correspond to a load angle of 20°.

The curves of Fig. 5, plotted from a complete family, show at the torque is, for the most part, proportional to the d.c. citation for a given load angle and a.c. supply. Similar conisions can be drawn for changes in a.c. supply, except that e relation between torque and applied alternating voltage for tor S shows somewhat greater departures from linearity over e upper part of the range. These results are broadly what ould be expected from a consideration of the vector locus, g. 2.

It would be difficult to give a precise account of performance ien the direct-current source is replaced by a rectifier. In this se the d.c. component produced is proportional to the alter-ting current supplied and there will therefore be an effective crease in d.c. excitation with load. The torque/load-angle rves will therefore be a combination of two families of curves, ie showing torque/load-angle curves for different applied ltages, and the other for different values of d.c. excitation. iey are found to be approximately linear, except for large load igles, as shown in Figs. 6 and 7. The torque might be expected



g. 6.—Torque/load-angle curves using rotors S and CW, and a rectifier in place of the battery in Fig. 1.

Curves D and E correspond to $V = 150$ and 250 volts, respectively. Curves inset ow the variation of torque with applied voltage for a load angle of 20°.

be proportional to the square of the applied voltage: the set graphs of Fig. 6 show that a slightly higher power than two involved.

(3.5) Power Factor and Efficiency

A most useful property of the orthodox synchronous motor is ie manner in which the power factor can be controlled by tering the d.c. excitation, and it is no less a marked feature of ie present application.

Consider, for example, the changes which take place when the irect current is increased, the alternating applied voltage and the ad angle being kept constant. Assuming that any conseuential changes in Z are small, the vector AB will remain fixed magnitude and direction but, as drawn in Fig. 2, will increase length. The power factor, cos BOD, is therefore increased.

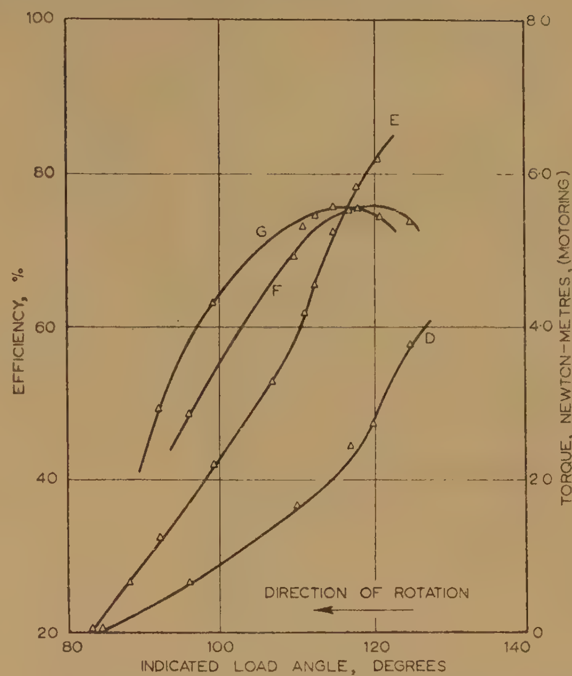


Fig. 7.—Half-speed synchronous performance with rotor SW, and with battery of Fig. 1 replaced by a rectifier.

D and E denote torque curves for $V = 200$ and 250 volts, F and G denote efficiency curves for $V = 200$ and 250 volts, respectively.

In graphical terms, the condition for unity power factor is that the circle AB should intersect OD. Thus, for given values of V and Z there is a value of d.c. excitation below which unity power factor is impossible.

Curves of power factor and θ_0 can be derived graphically from the vector locus, but a precise expression in trigonometrical terms is complicated. An approximate relation, derived in Section 9.5 [eqn. (20)], is

$$\text{Power factor} = \frac{\sin 2\theta_0}{\sqrt{(1 - 2\alpha \cos 2\theta_0 + \alpha^2)}}$$

where α is the non-dimensional parameter I_{AC0}/I_{DC0}.

This expression has a maximum value of unity only for $\alpha \leqslant 1 \cdot 0$ and for a particular value of θ_0 given by $\sin 2\theta_0 = \alpha$. When $\alpha > 1$, the maximum value is $1/\alpha$, and the corresponding value of θ_0 is given by $\sin 2\theta_0 = 1/\alpha$. Graphs of this function for different values of α, referred to as theoretical curves, are of the same general shape as those obtained in practice, except that the former are symmetrical and the latter are not. Adjusted theoretical curves derived from the vector locus more properly take into account the machine losses, which have the effect of increasing the power factor for positive values of θ_0 and reducing it for negative ones, thus producing the observed asymmetry. Practical and theoretical results are shown in Figs. 8 and 9. It was not thought necessary to quote more than two curves of a complete set for any one rotor in Fig. 8. Similarly, only one theoretical or unadjusted curve is shown in Fig. 9.

A concise expression for the efficiency cannot be quoted, as the losses in the machine are not calculable in simple algebraic terms. Practical results are shown in Fig. 10. It is always possible, of course, to derive the output torque by the methods described in the preceding paragraph, and to find the total alternating electrical input from the vector locus. To the latter must be added the power supplied from the direct-current source in arriving at a figure for the efficiency. As there are no back-e.m.f.'s at zero frequency, the direct-current power makes no

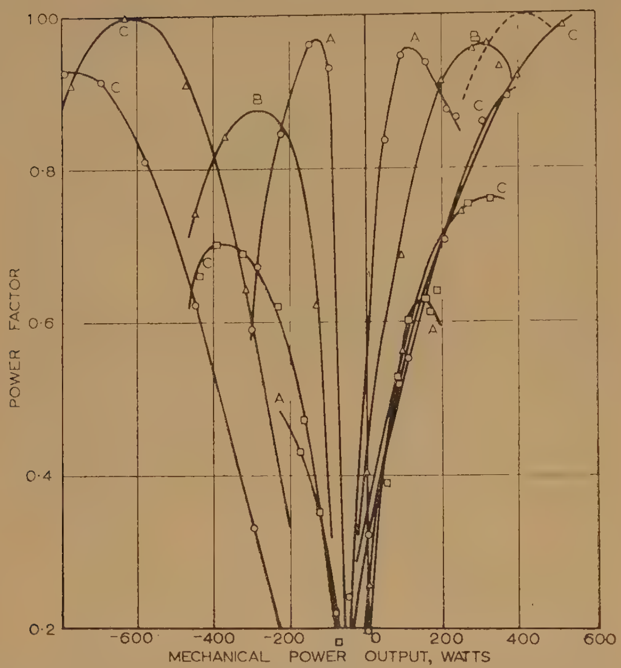


Fig. 8.—Half-speed synchronous operation: variation of power factor with load.

$V = 150$ volts. Symbols A, B and C correspond to $I_{DC} = 1\cdot0$, $1\cdot5$ and $2\cdot5$ amp, respectively. The broken line is part of the curve corresponding to $I_{DC} = 2\cdot0$ amp.

Rotor	I_{DC}	α	I_{DC}	α
S	1·0	2·5	2·5	0·99
CW	1·0	0·75	2·5	0·30
SW	1·5	0·73	2·5	0·43

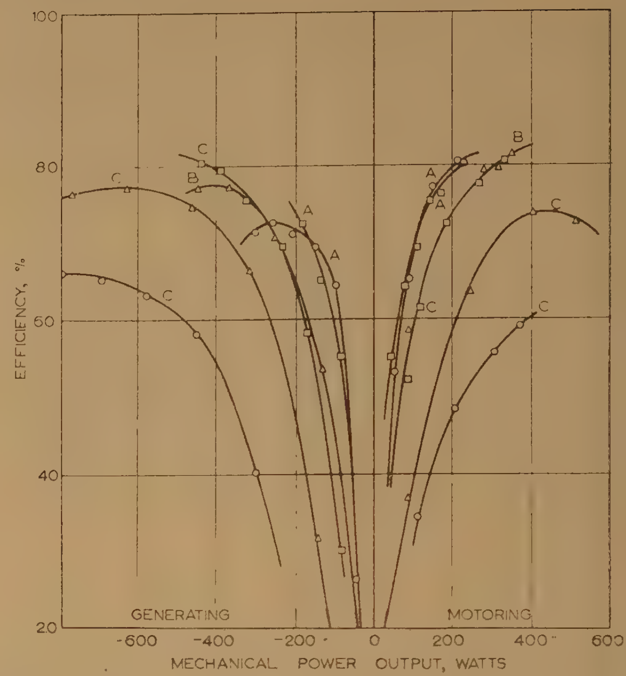


Fig. 10.—Half-speed synchronous operation: variation of efficiency with load.

$V = 150$ volts. Symbols A, B and C correspond to $I_{DC} = 1\cdot0$, $1\cdot5$ and $2\cdot5$ amp, respectively.

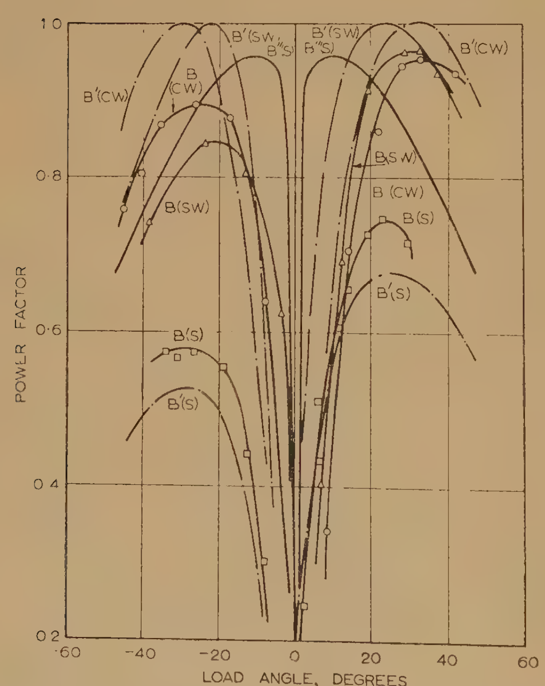


Fig. 9.—Comparison of theoretical and observed power factors.

$V = 150$ volts, $I_{DC} = 1\cdot5$ amp.

B and B′ refer to practical and adjusted theoretical curves, respectively. B″(S) is an unadjusted theoretical curve for rotor S. Symbols S, CW and SW identify a particular rotor. Values of α for rotors S, CW, and SW are 1·65, 0·5 and 0·73, respectively.

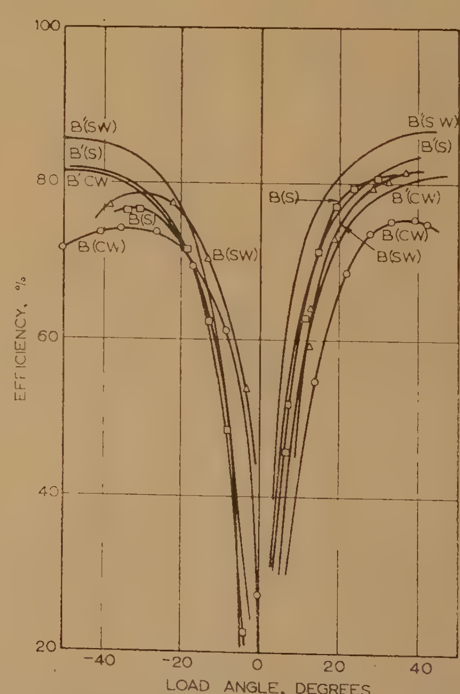


Fig. 11.—Comparison of theoretical and practical efficiencies.

$V = 150$ volts, $I_{DC} = 1\cdot5$ amp.

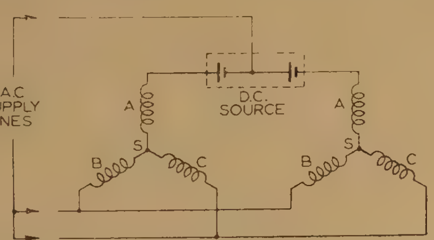
Symbols S, CW and SW identify the particular rotor used: B and B′ denote practical and adjusted theoretical curves, respectively.

ntribution to the output torque and is wholly dissipated as an mic-resistance loss. Any reduction in stator resistance is paid by a direct improvement in efficiency. Fig. 11 shows perimental and derived values of efficiency for the different pes of rotor. A third curve for each rotor could have been cluded to give some indication of the order of improvement hich might be expected from a reduction in stator resistance hich, for the machine employed, was higher than would have en chosen. It could be called the a.c. efficiency curve, as, in termining it, the d.c. power loss would be omitted completely. e improvement in maximum torque would be of the order of % for the salient rotor S and 2·5% for the two other rotors.

(4) D.C. EXCITATION

The presence of direct current in the a.c. supply system (Fig. 1) not desirable, and even when, as in the tests, a moving-coil gulator is used rather than a transformer, there is an upper nit imposed in practice to the d.c. excitation if the more extreme ects of saturation are to be avoided. Rectifiers in place of a ect-current source are better in this respect, and a number of cuits have been tried, but none was sufficiently superior to a ngle rectifier in one line to warrant the extra complication.

It is possible to devise circuits of the Wheatstone-bridge type order to exclude direct current from the a.c. supply, but they e complicated and not likely to be used in practice. Where o machines are employed in parallel, however, there is a mple solution. The circuit is shown in Fig. 12. It is required



g. 12.—Stator circuit connections for two motors to exclude direct current from the a.c. supply system.

at the potential difference between any two of the a.c. supply nes with respect to the d.c. line shall be zero. For this to be , the coil resistances should all be equal and the two direct-oltage sources should be equal. These conditions, once tablished, should not require frequent adjustment, since they not, for example, vary with load or rotor position and it is ot essential for the two machines to be equally loaded.* The inciple can be extended when there are more than two machines. Schenfer employed a separate stator winding to produce his c. excitation, and in series with it and the direct-current source connected a single-phase transformer energized from the main c. supply to balance out the e.m.f. induced from the 3-phase ator winding. This prevented alternating current from flowing rough the direct-current source, but no attention was given to e problem of direct current flowing in the secondary windings the balancing transformer.

A preferred method is one in which alternating current is cluded from the d.c. source and direct current from the a.c. ource. A circuit which achieves this has recently been devised nd is being tested.

(5) RUNNING-UP PERFORMANCE

Starting the half-speed synchronous motor presents no serious ifficulties, but conditions differ with the type of rotor used. The

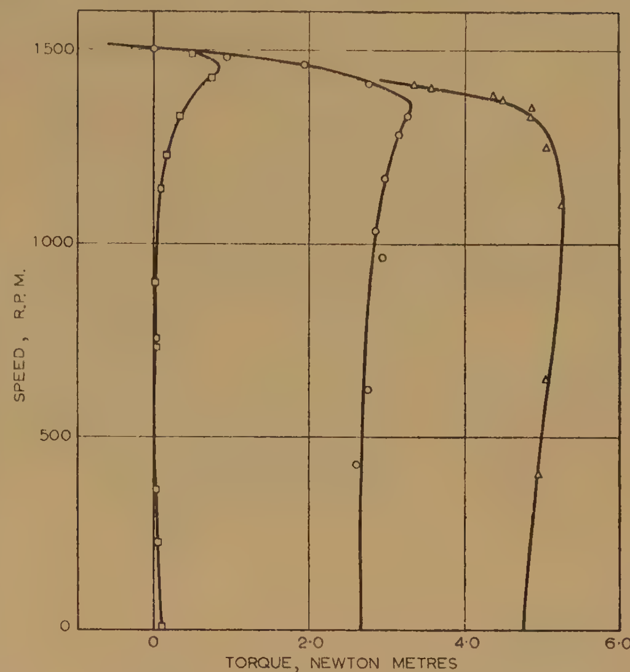


Fig. 13.—Torque/speed characteristics for different types of rotor when the 2-pole stator is connected directly to a 3-phase supply.
$V = 250$ volts.

torque/speed curves for the three rotors tested, with the d.c. excitation removed, are shown in Fig. 13.

That both the salient-pole and the cylindrical rotors with a short-circuited winding should possess an appreciable starting torque excites little comment. It is a matter of some surprise, however, that a salient-pole machine without rotor windings should be self-starting, and it is by no means obvious that there is an induction-motor effect in this case also. Very briefly, the explanation rests on the manner in which the rotor flux reacts with the stator windings. In this respect, it is an inverted induction-motor action, in which the stator winding is the secondary and plays the part normally assigned to the rotor in ordinary applications. It thus follows, from ordinary induction-motor principles, that the standstill torque is small for highly inductive windings, and that to improve the starting torque additional resistors are required in the secondary circuit. In the present application, starting resistors will probably be required, and they must be connected in the stator circuit but are otherwise employed in the usual way. The authors hope to give a more complete account on a future occasion.

Each of the three rotors will run stably at a speed somewhat less than half synchronous speed on an a.c. supply only, and if the d.c. excitation is then switched on, the rotor will be pulled into synchronism at exactly half synchronous speed.

A machine with a cylindrical rotor and a 3-phase rotor winding is perhaps the most versatile. In the ordinary way, i.e. without d.c. excitation, a rotor with an asymmetrically-connected 3-phase winding will start and run satisfactorily at a little less than half synchronous speed, as explained in the paper[2] already referred to. It corresponds to rotor CW in the present tests. When the stator d.c. excitation is switched on, or the rectifier is put in circuit to provide excitation, as in Fig. 1, the effect is to pull the rotor into exact half-synchronism. When, on the other hand, the 3-phase winding is used as such, there is no half-speed effect, and the machine will start in the usual way and run as an induction motor at a little less than synchronous speed, or as a

* There are a number of variations on this theme: the coils shown in Fig. 12 as e stator windings of a second machine could be replaced by a static network, and it not essential for the two d.c. sources to be the same.

*

Table 2

RUNNING-UP PERFORMANCE

<table>
<tr><th rowspan="3"></th><th colspan="2">Half speed</th><th colspan="2">Full speed</th></tr>
<tr><th>Asynchronous, $s > 0 \cdot 5$</th><th rowspan="2">Synchronous, $s = 0 \cdot 5$</th><th>Asynchronous, $s < 0 \cdot 5$</th><th>Synchronous, $s = 0$</th></tr>
<tr><th>No d.c. stator excitation</th><th colspan="2">No d.c. stator excitation</th></tr>
<tr><td>Salient rotor, S</td><td>Starting resistors desirable in the stator circuit</td><td rowspan="5">When the machine is running steadily at $s > 0 \cdot 5$, the d.c. excitation or equivalent rectifier is switched into the stator circuit and provides the synchronizing torque. Power factor control by varying excitation</td><td>Unstable, negative-torque region</td><td rowspan="2">Auxiliary drive required for running up between $s = 0 \cdot 5$ and $s = 0$</td></tr>
<tr><td rowspan="2">Salient rotor with windings, SW</td><td rowspan="4">Good starting torque with a single-phase or asymmetrically-connected 3-phase rotor winding</td><td>Unstable, negative-torque region for single-phase or asymmetrically-connected 3-phase rotor winding</td></tr>
<tr><td>Probably unstable with 3-phase winding. Torque may be positive or negative</td><td>Rotor excitation not essential. Self-synchronizing</td></tr>
<tr><td rowspan="2">Cylindrical rotor with windings, CW</td><td>Unstable, negative torque with single-phase or asymmetrically-connected 3-phase rotor winding</td><td rowspan="2">D.C. rotor excitation with single-phase or asymmetrically-connected 3-phase rotor winding: synchronous motor</td></tr>
<tr><td>Symmetrical 3-phase rotor winding: induction motor</td></tr>
</table>

synchronous motor if the direct current previously employed in the stator circuit is applied to the rotor windings reconnected asymmetrically. Much the same would be true of a salient-pole rotor with a 3-phase winding, except that it would not be essential to apply rotor excitation for the machine to pull into synchronism at synchronous speed. These conclusions are summarized in Table 2.

(6) CONCLUSIONS

The agreement between theory and practice is very satisfactory: surprisingly so in relation to the simplicity of the arguments advanced. Such differences as there are can be explained qualitatively in terms of non-linearity, hysteresis and eddy-current effects, and would be appropriately discussed in a more comprehensive investigation based on the information provided by the preliminary tests here described. For example, flux conditions in the rotor are different from those in both the ordinary synchronous motor and the induction motor. The rotor flux varies at half the supply frequency, instead of a small slip frequency, and losses arising from hysteresis and eddy currents assume a greater importance.

Because of the heavy rotor losses which would be incurred at half speed, a salient-pole synchronous motor of ordinary design and construction is not suitable for use as a 2-speed machine. With a special rotor, as shown in Fig. 14, a 2-speed machine is, however, a possibility. For a single speed, corresponding to half the supply frequency, a 4-pole machine of ordinary construction would be simpler and probably cheaper than a stator-fed machine, and would therefore be preferred in practice for ordinary purposes. For special purposes, e.g. when no rotor connections are permissible, the synchronous-machine characteristics of the half-speed motor could be usefully employed. Thus, for circulating corrosive liquids in a completely sealed system, all electrical connections to the pump motor must be outside the walls of the enclosure. The problem has hitherto been met by using a squirrel-cage motor in which the rotor is wholly enclosed and

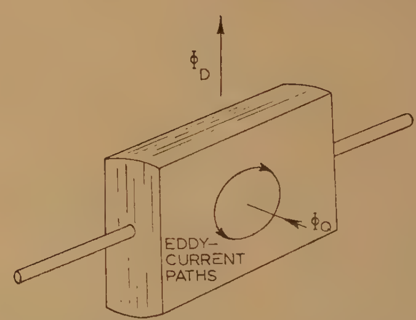


Fig. 14.—Schematic arrangement of rotor stampings to give an improved conversion ratio.

separated from the stator by a cylindrical shell which passes down the air-gap.[4] The efficiency and power factor of such motors are poor because of the large air-gap and the effect of eddy currents in the stationary shell, and some improvement could be achieved by using d.c. stator excitation.

The machine used for the tests employed stampings of ordinary magnetic quality, whereas, with the same shape of rotor, it would be possible to select a lower-loss material without departing from standard commercial grades, and some improvement could be expected by paying more attention to the insulation between stampings. A reduction in losses brings the usual rewards in improved efficiency, but the consequential changes in Z_D and Z_Q, though not so obvious, are at least as important.

The impedances Z_D and Z_Q are ultimately derived from fluxes set up in the direct and quadrature rotor axes, respectively, in the zero d.c. test. In any practical case, in which there are energy losses associated with these axes, Z_D and Z_Q will not be wholly reactive as they would otherwise be in the ideal case. It follows that if Z_D and Z_Q have an appreciable resistive component, the conversion ratio λ will be small. Thus, not only

will there be a negative displacement of the unadjusted torque curve, but the torque values before adjustment will be much reduced [as indicated in eqn. (4)].

As the behaviour of the machine depends essentially on the presence of d.c. excitation, it is not surprising that most of its special properties are summarized in the value of λ as defined in the zero a.c. test. Thus, a cylindrical rotor, for which the impedances in any two perpendicular directions are the same, does not display the half-speed effect. In this case, a short-circuited single-phase rotor winding reduces the effective flux in one direction and thus establishes a difference between the impedance along the coil axis and that at right angles to it. A similar device employed on a salient rotor, for which Z_D and Z_Q are initially different, will reduce the quadrature flux, and hence the reactive component of the quadrature impedance, still further. It is by no means certain that the net result will be an improvement. A decrease in Z_Q will be accompanied by an increase in λ, but the negative displacement corresponding to the inevitable additional ohmic losses may more than offset the increased torques which would otherwise be obtained. This explains why, on test results, there is not a great deal to choose between the salient-pole rotors with and without a short-circuited winding.

These arguments taken together suggest that, for stampings of a given material and thickness, an improved performance can be secured by employing a different rotor assembly. This would take the form of rectangular stampings in planes which are parallel to the axis of rotation, as shown in Fig. 14, instead of perpendicular to it, as is more usual. The value of Z_D will not be much changed by so doing, but there will be a considerable reduction in quadrature flux and hence in Z_Q, since the quadrature-axis magnetic circuit contains the high-reluctance paths between stampings in series. Moreover, the quadrature eddy currents will serve much the same purpose as short-circuited windings in tending to diminish the reactive component of the quadrature flux still further. There are, as yet, no test results for a rotor of this type, and it is possible that constructional difficulties may outweigh any advantages it may have, except for small machines which indeed have already been made in this way but for purposes quite different from the ones here discussed.

In the ordinary event, the impedances Z_D and Z_Q will have resistive and inductive components, and λ will be less than unity. This is not necessarily so if one of the impedances is capacitive and the other is inductive, for then the reactance components will be added in the numerator and subtracted in the denominator. Whether or not it is possible in practice to secure large values of λ in this way remains to be seen, but it is encouraging that in a similar, though admittedly not an identical, situation it was possible to increase the torque output by about 50% simply by using a capacitively-loaded coil on the direct axis.[1]

The paper has investigated the more important performance characteristics of the half-speed synchronous motor and has established guiding principles for future developments. The temptation to draw more precise conclusions than are warranted by the accuracy of the results, especially in relation to the imperfection in the test equipment, has been resisted. There were no marked differences between the performances of the three different rotors. Values of power factor and efficiency were good and higher values can be expected with improved rotor design. The single rectifier circuit shows promise and has the merit of simplicity.

(7) ACKNOWLEDGMENTS

The authors would like to put on record their appreciation of the facilities placed at their disposal in the Electrical Engineering Department of the University of Bristol, and of the interest shown by Professor G. H. Rawcliffe in this work. They are both indebted to the Department of Scientific and Industrial Research for the support given to one of them during the progress of the investigation.

(8) REFERENCES

(1) RUSSELL, R. L., and HODGES, N. W.: 'The Application of Counter-Rotating Fields to Electrical Measuring and Indicating Devices', *Proceedings I.E.E.*, Paper No. 1628 M, April, 1954 (**101**, Part II, p. 178).

(2) BARTON, T. H., and DOXEY, D. C.: 'The Operation of Three-Phase Induction Motors with Unsymmetrical Impedance in the Secondary Circuit', *ibid.*, Paper No. 1784 U, February, 1955 (**102**, Part A, p. 71).

(3) SCHENFER, C: 'Der Synchron-Induktionsmotor mit Erregung im Stator', *Electrotechnik und Maschinenbau*, 1926, **19**, p. 345.

(4) MEI, A. J.: 'Design and Operation of Small Canned Motor Pumps', *American Society of Mechanical Engineers*, 1954, Publication No. 54–A–120.

(9) APPENDIX

(9.1) General

With the connections as shown in Fig. 1, the axis of coil A and the direct-current field are coincident and defined to be $\pi/4$ in advance of the reference axis. Let coils B and C be so connected to the 3-phase supply that the m.m.f. rotates in an anticlockwise direction. In the absence of a d.c. supply, the asymmetrical rotor runs at a little less than half synchronous speed and the rotor flux has, as a consequence, a component which rotates with a small angular velocity $(1 - 2s)\omega$ with respect to the stator. The effect of superimposing the d.c. supply is to produce a stationary m.m.f. which provides a synchronizing torque and fixes the $(1 - 2s)\omega$ component in space, thus compelling the stator to run at $s = 0{\cdot}5$, i.e. at exactly half-synchronous speed. It follows that the alternating supply currents will be balanced, since the $(1 - 2s)\omega$ term is zero.

In order to express these statements quantitatively some method is required for expressing the saliency, or rotor asymmetry, in simple analytical terms. Three methods suggest themselves:

(*a*) To regard each stator coil as presenting an impedance to the supply which varies with the position of the rotor.

(*b*) To regard the stator coils as presenting a fixed impedance to the supply and to allow for asymmetry in terms of an additional stator-induced e.m.f.

(*c*) To regard the impedance Z presented to the supply as having three components: a stator-leakage impedance Z_s, a direct-axis impedance Z_D and a quadrature-axis impedance Z_Q.

The first is not very profitable and the second and third can be shown to be equivalent theoretically. They differ in the manner in which the parameters they employ can be found by simple practical tests, and, on these grounds, (*c*) is preferred.

(9.2) Zero D.C. Test

Consider first the special case in which the d.c. supply is reduced to zero and the rotor is driven at a half-synchronous speed in the field due to the a.c. supply only. At this speed, the negative-sequence currents, at a frequency $(1 - 2s)f$, which are normally reflected in the stator, will be zero, and the phase currents will therefore be balanced and at mains frequency.

It will be assumed throughout that the magnetic circuits are linear and that the stator winding is effectively sinusoidally distributed. Let Z and ϕ be the modulus and argument of the phase impedance and for coil A let

$$v_A = \sqrt{2}V \cos \omega t$$

Then

$$i_{AC0} = \sqrt{(2)}\frac{V}{Z}\cos(\omega t - \phi) = \sqrt{(2)}I_{AC0}\cos(\omega t - \phi) \quad (5)$$

where I_{AC0} denotes the r.m.s. alternating phase current in coil A when the d.c. supply is zero. There are similar expressions for coils B and C.

The three coil currents produce a constant resultant m.m.f. which rotates with uniform angular velocity ω with respect to the stator, or $\omega/2$ with respect to the rotor, and which, at any time t, is at an angle $\omega t - \phi$ to coil A, or $\omega t - \phi + \pi/4$ with respect to the reference axis. There is no reason, at this stage, to presuppose any particular position for the rotor, but for analytical convenience, as will be clearer later, let it be at an angle $\omega t/2 - \theta_0$. This means that the rotor is at an angle $-\theta_0$ at $t = 0$, or in other words that θ_0 is measured negatively from a position which is inclined at $-45°$ to the axis of coil A and the d.c. field. The direct-axis flux can be written

$$\Phi_D = \frac{3\sqrt{2}}{2}k_1N_1\frac{I_{AC0}}{S_D}\cos(\omega t/2 + \theta_0 - \phi + \pi/4 - \delta_D) \quad (6)$$

where S_D is the effective direct axis reluctance, δ_D is the corresponding loss angle, and k_1 is a winding factor used in converting phase m.m.f., N_1I_{AC0}, to stator m.m.f.

In a similar way, the flux in a direction perpendicular to the rotor, the quadrature flux, is

$$\Phi_Q = \frac{3\sqrt{2}}{2}k_1N_1\frac{I_{AC0}}{S_Q}\cos(\omega t/2 + \theta_0 - \pi/4 - \delta_Q) \quad (7)$$

where S_Q is the effective quadrature reluctance and δ_Q is its loss angle.

Each of the fluxes Φ_D and Φ_Q can be resolved into two equal components rotating in opposite directions with respect to the rotor to give, respectively,

$$\left.\begin{aligned} &\frac{3\sqrt{2}}{4}k_1N_1\frac{I_{AC0}}{S_D}\exp\left[\pm j(\omega t/2 + \theta_0 - \phi + \pi/4 - \delta_D)\right] \\ \text{and } &\frac{3\sqrt{2}}{4}k_1N_1\frac{I_{AC0}}{S_Q}\exp\left[\pm j(\omega t/2 + \theta_0 - \phi - \pi/4 - \delta_Q)\right] \end{aligned}\right\} \quad (8)$$

To obtain flux components referred to the stator, the first of these expressions must be multiplied by $\exp[j(\omega t/2 - \theta_0)]$ and the second by $\exp[j(\omega t/2 - \theta_0 + \pi/2)]$, giving

$$\frac{3\sqrt{2}}{4}k_1N_1\frac{I_{AC0}}{S_D}\{\exp[j(\omega t - \phi + \pi/4 - \delta_D)] + \exp[j(\phi - 2\theta_0 - \pi/4 + \delta_D)]\} \quad (9)$$

$$\frac{3\sqrt{2}}{4}k_1N_1\frac{I_{AC0}}{S_Q}\{\exp[j(\omega t - \phi + \pi/4 - \delta_Q)] + \exp[j(\phi - 2\theta_0 + 3\pi/4 - \delta_Q)]\} \quad (10)$$

The variable component of flux linkages in coil A is

$$\frac{3\sqrt{2}}{4}k_1N_1N_2I_{AC0}\left[\frac{\cos(\omega t - \phi - \delta_D)}{S_D} + \frac{\cos(\omega t - \phi - \delta_Q)}{S_Q}\right]$$

In vector form this last expression is, from eqn. (5),

$$\frac{3}{4}k_1N_1N_2\left(\frac{1}{S_D} + \frac{1}{S_Q}\right)I_{AC0}$$

The induced e.m.f. in coil A is therefore

$$-j\left(\frac{3}{4}\omega k_1N_1N_2\right)\left(\frac{1}{S_D} + \frac{1}{S_Q}\right)I_{AC0} \quad . \quad . \quad . \quad (11)$$

It will be observed that the induced e.m.f. is independent of the initial position of the rotor, θ_0.

If Z_s is the stator leakage impedance per phase at the supply frequency, i.e. the combined resistance and leakage reactance, then

$$I_{AC0}Z_S = V - j\frac{3}{4}k_1N_1N_2\omega I_{AC0}\left(\frac{1}{S_D} + \frac{1}{S_Q}\right) \quad . \quad (12)$$

$$I_{AC0} = \frac{V}{Z} = \frac{V}{Z_S + Z_D + Z_Q} \quad . \quad . \quad . \quad (13)$$

where $$Z_D = j\frac{3}{4}k_1N_1N_2\omega\frac{1}{S_D};\ Z_Q = j\frac{3}{4}k_1N_1N_2\omega\frac{1}{S_Q} \quad . \quad (14)$$

and the overall stator impedance is $Z = Z_S + Z_D + Z_Q$.

When the direct and quadrature m.m.f.'s are exactly in phase with the direct and quadrature fluxes, respectively, then S_D and S_Q will be wholly real and both Z_D and Z_Q will be wholly reactive. In fact, the flux and m.m.f. will not be in phase if only because of eddy-current and hysteresis effects, and therefore Z_D and Z_Q will have resistance terms, which may or may not be small, corresponding to the losses along the direct and quadrature axes respectively.

From readings of current, voltage and power in a test under the above conditions, Z can be found in both modulus and argument.

(9.3) Zero A.C. Test

Corresponding to the special case of the previous paragraph there is another one in which the a.c. supply is reduced to zero and the rotor is driven at half synchronous speed, $\omega/2$, in the field due to the d.c. supply alone. In principle, this is similar to the inductor alternator, and balanced alternating currents of angular frequency ω will flow in the stator coils. The phase of the stator-induced e.m.f. is not, in this case, independent of the initial rotor position, θ_0.

With the same notation as before, the direct- and quadrature-axis fluxes, respectively, due to the d.c. excitation only, are

$$\frac{3}{2}\frac{k_1N_1I_{DC}}{S_D}\cos(\omega t/2 - \theta_0 - \pi/4 - \delta_D)$$

and

$$\frac{3}{2}\frac{k_1N_1I_{DC}}{S_Q}\cos(\omega t/2 - \theta_0 + \pi/4 - \delta_Q)$$

Resolving each of these fluxes into its two components, exactly as before, and referring them to the stator, we obtain, respectively,

$$\frac{3}{4}\frac{k_1N_1I_{DC}}{S_D}\{\exp[j(\omega t - 2\theta_0 - \pi/4 - \delta_D)] + \exp[j(\pi/4 + \delta_D)]\}$$

and

$$\frac{3}{4}\frac{k_1N_1I_{DC}}{S_D}\{\exp[j(\omega t - 2\theta_0 + 3\pi/4 - \delta_Q)] + \exp[j(\pi/4 + \delta_Q)]\}$$

The time-varying component of flux linkages in coil A is

$$\frac{3}{4}k_1N_1N_2I_{DC}\left[\frac{\cos(\omega t - 2\theta_0 - \delta_D - \pi/2)}{S_D} + \frac{\cos(\omega t - 2\theta_0 - \delta_Q + \pi/2)}{S_Q}\right]$$

or, in vector form,

$$-\frac{3}{4}k_1N_1N_2I_{DC}\left(\frac{1}{S_D} - \frac{1}{S_Q}\right)$$

where I_{DC} is a vector corresponding to the instantaneous value $I_{DC}\cos(\omega t - 2\theta_0 + \pi/2)$. The modulus of I_{DC} is $\frac{1}{\sqrt{2}}I_{DC}$.

The induced e.m.f. in coil A is then

$$+j\frac{3}{4}k_1N_1N_2\omega I_{DC}\left(\frac{1}{S_D}-\frac{1}{S_Q}\right)=+(Z_D-Z_Q)I_{DC} \quad . \quad (15)$$

Using I_{DC0} to denote alternating current due to the direct-rrent supply only, and using the results of Section 9.2,

$$I_{DC0}=\frac{\text{e.m.f.}}{Z}=\frac{Z_D-Z_Q}{Z}I_{DC} \quad . \quad . \quad . \quad (16)$$

$$i_{DC0}=\lambda I_{DC}\cos(\omega t-2\theta_0+\pi/2-\eta) \quad . \quad . \quad (17)$$

here λ and η are the modulus and argument, respectively, of e complex quantity $\frac{Z_D-Z_Q}{Z}$.

Thus the phase of I_{DC0} depends on θ_0 and, furthermore, by easuring I_{DC} and I_{DC0}, the modulus of $\frac{Z_D-Z_Q}{Z}$ can be found. nce Z is known from the previous test, $|Z_D-Z_Q|$ can be etermined if required.

(9.4) Half-Speed Synchronous Machine: Vector Locus

Assuming linear magnetic circuits, the resultant supply current, in any one stator coil when both alternating- and direct-current pplies are employed, is the sum of the separate currents btained when either of the supplies is used alone. Thus, from ns. (5) and (17).

$$\begin{aligned} &= i_{AC0}+i_{DC0}\\ &= \sqrt{(2)}I_{AC0}\cos(\omega t-\phi)+\sqrt{(2)}I_{DC0}\cos(\omega t-2\theta_0+\pi/2-\eta) \end{aligned} \quad . \quad . \quad . \quad . \quad . \quad (18)$$

here $I_{AC0}=\frac{V}{Z}$ and $I_{DC0}=\frac{\lambda}{\sqrt{2}}I_{DC}$.

The first term of eqn. (18) is fixed, and the second term repre-nts a vector of constant length, proportional to I_{DC}, whose osition relative to the voltage vector is $-2\theta_0+\pi/2-\eta$.

Fig. 2 is a circle diagram representing eqn. (18) in vector form. is now clear that θ_0 is closely related to the load angle of the achine and differs from it only by the constant η. A retarding rque applied to the rotor, corresponding to an increase in θ_0, oduces an increase in supply current. A driving torque, on e other hand, decreases θ_0, and the machine may well behave a generator.

As a first approximation in what follows, the losses in the achine will be assumed to be small, and, as a direct consequence, and η can be taken as $\pi/2$ and zero, respectively. This is not e crude approximation it might appear to be, and does not lead nugatory conclusions which would follow, for example, if the me assumptions were made for the induction motor, where tor losses are essential for its performance.

The load angle in this case is θ_0, since no-load conditions are btained when I and V are in quadrature, i.e. when $\theta_0=0$. This the position in which the rotor lies 45° behind coil A at $t=0$ nd, of course, at corresponding instants of time in subsequent cles of the supply voltage. The machine behaves as a motor r positive values of θ_0, i.e. for AB on the right-hand side of OA, nd as a generator for negative values of θ_0, when AB lies on the left-hand side of OA. Values of $2\theta_0$ exceeding 90° corre-spond to unstable operation.

(9.5) Power Factor and Current

The power factor, which is cos BOD, varies with both the load and the d.c. excitation. The geometrical condition for unity power factor is simply that the circle AB should intersect the line OD. Points on the arc above OD correspond to a leading power factor. If the circle intersects a line through O perpendicular to OD, the power factor will change sign, corre-sponding to the machine behaving as a generator.

From the vector triangle OAB, now assuming negligible losses,

$$I^2=I_{AC0}^2+I_{DC0}^2-2I_{AC0}I_{DC0}\cos 2\theta_0 \quad . \quad . \quad (19)$$

and the power factor is given by

$$\frac{I_{DC0}}{I}\sin 2\theta_0=\frac{\sin 2\theta_0}{\sqrt{(1-2\alpha\cos 2\theta_0+\alpha^2)}} \quad . \quad . \quad (20)$$

where α is $\frac{I_{AC0}}{I_{DC0}}$.

The maximum value of power factor given by eqn. (20) is unity, for $\alpha \leqslant 1$, and the corresponding load angle is given by $\cos 2\theta_0=\pm\alpha$. For $\alpha \geqslant 1$, the maximum value of power factor is $1/\alpha$, and the corresponding load angle is given by $\cos 2\theta_0=1/\alpha$.

(9.6) Torque

On the assumption of negligible losses, the electrical input is converted wholly into torque. Therefore, from eqn. (20),

$$T\frac{\omega}{2}=3IV\frac{I_{DC0}}{I}\sin 2\theta_0$$

$$T=\frac{6VI_{DC0}}{\omega}\sin 2\theta_0 \quad . \quad . \quad . \quad . \quad (21)$$

To derive a more realistic expression for torque, some allowance must be made for losses. A precise calculation is desirable but impracticable, and a first step is to measure the light-load losses and to assume that they remain constant. If P represents the light-load losses per phase, the torque will be given by

$$\begin{aligned} T&=\frac{6}{\omega}(IV\cos \mathrm{BOD}-P)\\ &=\frac{6}{\omega}[I_{AC0}V\cos\phi+I_{DC0}V\sin(2\theta_0+\eta)-P]\\ &=\frac{6}{\omega}[(I_{DC0}V\sin(2\theta_0+\eta)-(P-I_{AC0}V\cos\phi)] \end{aligned} \quad (22)$$

This shows that the torque/displacement curve will be sub-stantially the same as in eqn. (21), but displaced negatively by an amount $\frac{6}{\omega}(P-I_{AC0}V\cos\phi)$, so that, whilst the peak-to-peak values remain unchanged, motoring torques are diminished and generating torques are increased.

DISCUSSION ON
'THE ELECTRICAL ENGINEERING INDUSTRY IN THE POST-WAR ECONOMY'*

Before the EAST MIDLAND CENTRE, *at Loughborough, 22nd November,* 1955, *and the* NORTH MIDLAND CENTRE, *at Leeds, 3rd January,* 1956.

Mr. W. Fenwick (*at Loughborough*): In Section 2.1, the author states, 'For some years now we have imported more than we have exported in the form of finished goods, and if the present standard of living is to be maintained there must be a great and rapid increase in production and in the efficiency with which we use the resources at our disposal'. It has always been difficult to determine how long we could continue as a nation to operate with this wide difference between imports and exports, called an unfavourable balance of trade, since we were advised that most of our assets abroad and resources had been liquidated to pay for the cost of the First and Second World Wars. Yet in the same Section the author states that 'At present we are living within our means, but the outlook is uncertain because of the limited resources at our disposal'. Would he amplify these statements?

Fig. 2 indicates that one of the ways whereby our economy can be improved is in increasing the growth and production of food in this country, and here again the electrical industry can be of considerable help.

In Section 3.1 reference is made to the great advance in the development of simpler and more effective techniques which were intended to pay for their installation by increased productivity and by the release of labour for other, and presumably more important, work. I think it would be more true to state that these more effective techniques have come about not to release labour but because of the shortage of labour; and one of the advantages of full employment is that it brings into being new and more effective production techniques.

In Section 3.1.3 reference is made to the fact that increased production has to be disposed of before it can contribute to our economic welfare, and the author draws specific attention to the increasing difficulty of disposing of this increased production oversea. One incentive to an increase in oversea trade would be a reduction in taxation for such business, which would then permit the manufacturers making the largest contribution to increase their reinvestment in the oversea business and so further to enlarge their production facilities for oversea disposal.

With regard to research and development, it is agreed that there is a great need in this country for application engineers, and it is hoped that closer liaison between the supply and manufacturing industry will enable us to meet this need in the future.

On the question whether research should be in electrical appliances or heavy plant, there is the other aspect that many of the younger industrial nations are able to copy appliance designs, but they have not got the specialist knowledge on heavy plant, and it may be in our interests to continue with the major research in heavy engineering rather than in the lighter appliances.

Finally, because we are not self-supporting in food and raw materials, do we not need, in addition to more production, to encourage emigration, particularly to those areas of the Commonwealth where it is possible to contribute to an increase in food and material resources?

Mr. A. J. Barter (*at Loughborough*): If I had worked later this evening, instead of attending the meeting, would anyone be better off? The answer is 'No', except perhaps that I should not have had so much work to do in the morning. One difficulty is that, as the team in which we work has grown larger, until it now consists of the whole nation, we have overreached the yar stick by which to judge the individual contributions to the overa statistics. How are we to bring the figures in the paper back the individuals that go to make them up?

Mr. A. J. Coveney (*at Leeds*): The increasing growth of t electrical industry continues each year to take more of t country's capital, labour and raw materials. It must therefo contribute a larger share of the country's export business, as o economic future depends on the export of manufactured good The nation's wealth in raw materials of coal and iron h diminished to the extent that we now import these commoditie The output of manufactured goods relies upon the supply these materials, and shortages and increase in cost will increa the price of electrical energy to the industry and the price manufactured goods.

The electrification of coal mines has not materially increase production, and I agree with the author that benefits fro materials, human efforts and increased productivity have bee spent in providing easier conditions for workers. It appears th the acceptance of these new methods has provided more leisu and not assisted the national economy.

All economic considerations depend on the law of supply an demand, and with regard to labour, the demand since the wa has exceeded the supply. Higher school-leaving age and tw years' national service have caused management to have a seve labour problem, and we must make the maximum use of th labour available and prevent any losses by every effort.

One significant fact of this post-war period of great socia change has been the failure to prevent stoppages and disputes b negotiations. Fig. B shows the aggregate number of workin days lost during the last ten years.

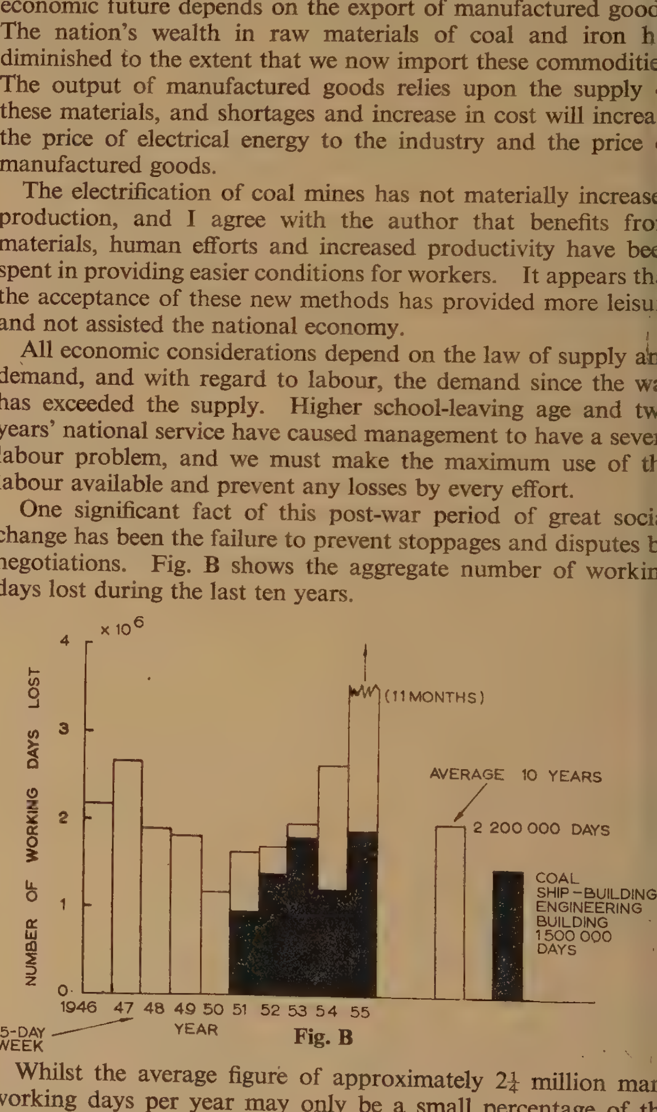


Fig. B

Whilst the average figure of approximately 2¼ million man working days per year may only be a small percentage of the total population working days, it is a costly one to industry, a these stoppages also affect other industries and the community as a whole. The proportion shown in black represents the stoppages in the coal, ship-building, engineering and building industries. There is a decline to 1950 and a rise since. This may possibly have a political significance.

To appreciate the national economic position simply, we nee

* METZ, G. L. E.: Paper No. 1795, February, 1955 (see 102 A, p. 772).

Table B.—BALANCE OF TRADE

United Kingdom imports	1938	1950	1951	1952	1953	1954
	$£10^6$	$£10^6$	$£10^6$	$£10^6$	$£10^6$	$£10^6$
Food, drink and tobacco	432	1 030	1 294	1 212	1 319	1 331
Raw materials	251	995	1 710	1 398	1 284	1 354
Manufactures	236	566	884	849	723	694
Total ..	919	2 591	3 888	3 459	3 326	3 379

United Kingdom exports	1938	1950	1951	1952	1953	1954
	$£10^6$	$£10^6$	$£10^6$	$£10^6$	$£10^6$	$£10^6$
Food, drink and tobacco	38	135	161	158	152	151
Raw materials	58	105	95	111	122	253
Manufactures	376	1 883	2 273	2 233	2 219	2 263
Total ..	472	2 123	2 529	2 502	2 493	2 667
Excess imports over exports	447	468	1 359	957	833	712

…ly look at the published figures for balance of trade given in Table B. These indicate an excess of imports over exports in pre-war days of £447 million, whereas in 1951 the difference was three times that amount.

It will be seen that, since 1951, a steady improvement in the balance has been obtained owing to the increase in the export of manufactured goods, although the imports of food, beverages and raw materials still continue to rise.

The author is a little unjust in his ratio of the industry's contribution to research and development. The major portion of the £200 million spent has surely been given to atomic research, nuclear power and armament developments. The electrical industry has always met the major cost of developments, and the installation of short-circuit testing stations, high-voltage and experimental laboratories is proof of the long-term plan and wise spending of the British manufacturer, to enable him to meet expanding demands of both home and foreign markets. In comparison with the United States, we must not be too modest, for we continue to make the best ships and the best aircraft, and continue to lead in new developments—stainless steel and Polythene are examples which justify our research costs.

The need in the future is a high-level direction to use our capital to the best advantage, to eliminate waste, inefficiency, extravagance and excess profits, and to encourage all classes of labour to understand, from the national economic point of view, the need to produce more.

Mr. N. Ashton (*at Leeds*): The essence of the paper is that of increased national income and the contribution which our industry can make to that activity. I accept the significance of the term 'national income' as a measure of greater economic advantage to the nation. In many ways our industry can contribute largely in these days, particularly in the matter of capital goods for export, since many countries do not now require consumer goods, simply because they can manufacture them themselves.

With the shortage of raw material, it seems to me that we should make the resources available to those branches of the industry which can secure maximum results. I can best illustrate this idea by saying that if we sell a ton of metal in the form of a motor car, our exports benefit by about £400, but if we sell a ton of metal in the form of aircraft, then we secure no less than £25 000. It is very much a case of selling ideas.

I think it would have been helpful if the author had shown in Fig. 2 the amount of capital that has been poured into industry in order to achieve the results indicated. Expansion can be easily achieved by pouring capital and manpower into any project, but at present a balanced programme is called for, in order to produce the maximum results from the resources available.

In Section 3.1.2 the author expresses the belief that certain psychological difficulties will be overcome. Could he expand on this theme and state how he believes they will, in fact, be overcome?

Whilst the author concludes on a rather pessimistic note, I believe that we must all be optimists in this matter, and that in this country we have sufficient moral fibre and brain power to overcome these problems, provided that we have the will to apply them.

Mr. G. L. E. Metz (*in reply*): So many questions have been raised in the discussions that it is quite impossible to deal with them adequately in the space at my disposal. I have therefore considered what it is we have been seeking from this investigation into the electrical engineering industry in the post-war economy and what progress has been made toward this objective in our discussions.

The paper records the remarkable advance made by the industry since the first review in 1946. Production has gone racing ahead; exports are fast approaching the staggering figure of £250 million annually: employment has been increasing by some 50 000 people each year to reach a total of nearly one million. The industry has, from a minor position, become one of the leading characters on the stage of national affairs. This has happened in a period of increasing difficulty in the sphere of world affairs, and although many thought when the paper was first read in London that these difficulties had been over emphasized, experience has since shown that this was not so.

Behind much that has been said in the discussions lay the knowledge that the tide of world affairs is creating difficulties for our country in the military and economic fields. These difficulties may be ephemeral but could threaten our very existence as a great power and our position at the centre of a great Commonwealth. If Britain is to remain great she must rebuild her economic strength, and for a manufacturing nation that means that productivity here must be greater than in the countries with which we compete. It is the members of this Institution who hold one of the keys to increased productivity, and on them therefore depends to a large extent whether this country goes forward or back.

Among a host of valuable suggestions made in the discussions, one point was made which I feel may affect The Institution, its members and the industry it serves more than any other. It is that the industry is now so important and so influential that it can no longer ignore the effect and consequences of its acts on other industries and upon the economy and society in general. When engineers produce something that will increase productivity they should not ignore the fact that it may, if clumsily applied, cause serious unemployment and misery among their fellows. When they produce a new weapon they should not ignore the possibility of some one, with less knowledge of the consequences, using it in ways that will bring disaster to all.

The Institution is already responding to these new responsibilities, and will, I believe, in future find itself to an ever-increasing extent having to watch the new developments in the industry, having to study their effects on other industries, on employment and in the social and economic fields generally, and having to guide its application so that transition stages are gentle rather than violent, and so that the good effects are obtained without the bad ones.

DISCUSSION ON 'DESIGN, PERFORMANCE AND APPLICATION OF MINIATURE CIRCUIT-BREAKERS'*

Before the North Midland Utilization Group, *at Leeds*, 18*th October, and the* Mersey and North Wales Centre, *at* Chester, 24*th October*, 1955.

Mr. E. Ellis (*at Leeds*): I should like more information on the performance of miniature circuit-breakers on repeated closure under conditions of 75% overload at low power factor and also under short-circuit conditions. How often in a given period will they operate successfully under such conditions? The unit is sealed, and one cannot inspect the damage after operation under severe conditions; the circuit-breaker will probably close after such operation, but be in such a condition as to fail when next called upon to operate. One might be tempted to leave it in circuit on the assumption that it will withstand further operations, but it is an unknown quantity that is being risked.

It may not be easy to estimate the fault power at points beyond the consumer's terminals in deciding whether back-up protection is necessary.

Have the losses and contact voltage-drop been measured after a circuit-breaker has operated a few times under fault conditions, and are figures available for any increase or decrease?

On the question of switching surges, I cannot reconcile the exception cited, namely 'heating appliances having a high initial resistance', and wonder whether it is the reactance of the spirally wound elements which makes these the exception. In view of the small contact gap, how do miniature circuit-breakers behave on a purely capacitive load?

In a properly designed installation the protective gear should be selected and graded so that operation occurs only under defined fault conditions. The authors infer that fuse rupture occurs quite often on all installations, but with correct practice the operation of protective gear is a comparatively rare occurrence.

Miniature circuit-breakers have a relatively large number of moving parts and springs: will they be effective after being inactive for many months when installed in adverse conditions as is experienced in practice, e.g. damp or heat, with both internal and external condensation? The mechanism may be seized and operation impossible.

Is it to be assumed that miniature circuit-breakers cannot be misused or interfered with?

Correctly selected h.r.c. fuses should protect against heavy short-circuit fault conditions, and a motor starter should be capable of protecting the motor. I cannot readily agree that, with the correct starter having correct overload settings, h.r.c. fuses are entirely unsuitable for such applications.

It is well to state that graded protection of any type should be applied throughout an installation to achieve accurate discrimination.

The authors compare the costs of switch-fuses and h.r.c. distribution boards with the cost of similar m.c.b. units. The costs should also be compared with the popular, but not necessarily approved, rewirable fuse distribution boards.

It would seem from the authors' comments that the replacement of fuses, etc., is a most expensive item, but caution should be exercised on this point. Even with correctly designed installations and selected protection an electrician should be called in where fault conditions are suspected. Is the position with miniature circuit-breakers very much different?

The statement that the smaller the number of fuses in an installation, the greater the saving in maintenance, applies equally to m.c.b. protection.

Mr. J. Tattley (*at Leeds*): Complete schemes have been developed and used in schools, public buildings and flats: for example, a conventional ironclad switchboard some 12 ft in length was replaced by an m.c.b. cubicle approximately 2 ft 8 in long, thus affording a considerable saving in space which the architect was able to use for other purposes. The cubicle comprised multiways of miniature direct-breakers controlling circuit boards of smaller miniature circuit-breakers situated throughout the buildings in place of fuseboards, the only fuses used throughout the installations being the 3, 7 or 13 amp cartridge type inserted as required in the 13 amp switched socket-plug tops, for protection of the apparatus used on these circuits.

The use of miniature circuit-breakers in flats and dwellings for domestic consumers has proved highly satisfactory, especially on the 13 amp ring circuits for sockets, since when faults developed on kettles, irons, vacuum cleaners and other domestic apparatus, circuit-breakers prevented the misuse and abuse of circuit fuses which the consumer was inclined to rewire and overload in the hope of rectifying the fault on the apparatus. Similarly, in schools and other buildings miniature circuit-breakers for overload protection have proved very satisfactory. In one case they prevented the installation, by an unauthorized person, of a 4 kW immersion heater in place of a 3 kW heater, which would have overloaded the installation. Had the circuit been fused in the conventional manner, the fuses would no doubt have been strengthened beyond the point originally intended, with consequent damage to the installation as a whole.

Mr. A. R. Rumfitt (*at Leeds*): In reviewing the merits of the applications for miniature circuit-breakers, a comparison must inevitably be drawn with the performance to be expected from fuses as the only alternative in the types of system under review. In making such a comparison we see at once that a similar conflict occurs on e.h.v. systems in the protection of power transformers up to 750 kVA. In this latter case, however, oil circuit-breakers are the established method of control, and endeavours have recently been made to justify the use of e.h.v. fuses mounted in their associated switch-fuse units. Three factors have to be considered when analysing the ideal switching and protective arrangement, namely

(*a*) The reproducibility of test results.

(*b*) The ability to test the routine overload performance of the device.

(*c*) The realization that in order to avoid undue system surges the ideal device will operate at current zero on an a.c. system.

From this it will doubtless be agreed that any circuit-breaker is unchallenged on points (*a*) and (*b*), since a fuse test can be regarded only as a type test and the assumption made that such performance is typical of the batch from which the sample selection was made. Type tests and routine tests can be made on any circuit-breaker sample, while accurate calibrations of overload performance can be made.

* Wolff, H. W., and Atherton, T. G. F.: Paper No. 1745 U, December, 1954 (see 102 A, p. 364).

While the foregoing would tend to suggest that the miniature circuit-breaker could be accepted without question, the authors have stressed its limited short-circuit capacity as made at the moment. I do not feel, however, that their argument in Section 5.4 is very sound, since very few circuit-breakers have been assigned 60 and 100 amp ratings to B.S. 936, Table 4. In the minds of potential users the rating of 1 MVA per pole per phase will inevitably be compared with the available rating of 25 MVA in conventional h.r.c. fuses.

The authors have tried to make a case for accepting the limited short-circuit capacity of the miniature circuit-breaker on the basis that in practice fault levels rarely exceed 3–5 kA. This is misleading, for the prospective fault level is a function of the types of installation which have been used as the basis of this analysis. In the true industrial substation, fault levels of the order of 25 MVA are frequently experienced, owing to the short physical distance between the incoming transformers and the l.v. distribution system. In conventional switch-fuse gear the busbars are connected to the incoming transformer by short lengths of cable; hence the fault level on the busbar system is of a high order. In view of the superiority of the miniature circuit-breaker in its overload performance, the authors should concentrate on improved short-circuit performance in order that their device may be truly competitive with the available fuse performance.

Mr. J. R. Harbottle (*at Leeds*): Section 7 is based upon the comparison in price between a miniature circuit-breaker and a switch-fuse. Surely the latter should include its associated toggle switch? I appreciate that this concept of the application of miniature circuit-breakers differs from the existing domestic and industrial practice in this country. Has their use in North America or on the Continent caused the adoption of a standard practice in which the functions of load switching, overload and fault protection are combined in one unit?

Mr. B. V. Dightam (*at Leeds*): The authors discuss the compensation of thermal elements for ambient temperature variation. Is this the practice of the majority of manufacturers, for in a number of industries temperature compensation is of considerable importance?

Mr. H. Moss (*at Leeds*): Has consideration been given to the use of small mercury switches, or are there any circuit-breakers embodying them? They might be preferable to hard metal contacts, especially in dirty or damp positions. From my experience of domestic installations and the faults that have occurred on them I am not in favour of miniature circuit-breakers, because in most cases it is preferable to find and remedy the fault before attempting to close the circuit.

I have known many domestic installations that have not had a fuse rupture in 40 years: the installations were done by competent workmen and not interfered with by amateurs and others. Generally speaking, fuses are adequate for the protection of domestic installations without adding to the initial cost by substituting circuit-breakers for fuses. There are many commercial and industrial installations where it might be good policy to consider the fitting of circuit-breakers, but they are unnecessary for domestic circuits.

Mr. E. Jacks (*at Chester*): I cannot agree that the field is as wide as the authors seem to imply. In Section 5.4 they say, 'It has already been pointed out that prospective fault currents exceeding the capacity of miniature circuit-breakers are the exception rather than the rule in sub-circuits'. While it may be true that many sub-circuits have a low fault level, it does not follow that sub-circuits with higher fault levels are by any means the exception.

In a provincial town in the north-west the 11 kV system is fed into a substation having two 1 MVA transformers in parallel, and is then fed out again to satellite substations, one having a 500 kVA transformer and the other a 1 500 kVA transformer, the fault levels being 30·5, 11·4, 27·6 MVA respectively. The two 1 MVA transformers are situated under a market building, so that the shops and market stalls connected to it are electrically very close to the transformers. On the authors' evidence there is no doubt that the fault level on these premises is likely to exceed by many times that which miniature circuit-breakers can deal with adequately. The same argument will also undoubtedly apply to premises adjacent to the 500 kVA transformer.

This system is typical of networks throughout the country. Transformers up to 1 MVA capacity are used in very large numbers, and larger capacities will undoubtedly continue to be used where space is at a premium and where it is easier and cheaper to put in a large transformer rather than several small ones. Since h.r.c. fuses are readily obtained at an economical price for rupturing capacities of 35 MVA and above, the higher fault levels resulting from the larger transformers raise no difficulties from the aspect of short-circuit protection.

Concerning the distribution system shown in Section 6.4, it should be remembered that it is the point at which the circuit is interrupted which needs to be of adequate rupturing capacity. Conversely, it is necessary to guarantee that the circuit will always be interrupted at a point where adequate rupturing capacity exists. It is not clear from the paper whether the authors are satisfied that these conditions can be met by the use of miniature circuit-breakers.

Mr. H. Funke (*at Chester*): Would the authors advise the generally recommended derating factor of miniature circuit-breakers when used at high ambient temperatures? Furthermore, what will be the effects of tropical climates, etc., on their performance?

A warning must be given when the circuit-breakers are to be used for relay-circuit protection: they lack the cut-off feature of h.r.c. fuses and may pass sufficient fault current for closed relay contacts to weld together. The use of a load-limiting resistor would overcome this disadvantage, but being an additional item, would defeat the simplicity of a fuse. The thermal overload, which has an inherent memory of the approximate heat in the motor, is desirable, particularly as allowance must be made for the preponderance of unskilled operatives.

Prolonged continuation of repetitive inching of a loaded motor should be prevented by the overload device, unless steps are taken to limit the starting-current peaks or the motor is rated for such duty.

Regarding the inaccuracy of solenoid overloads, the sealed electromagnetic time-delay unit is small, and therefore the tolerances required for mass-production will be proportionately large; furthermore, there is usually considerable variation in mass-produced springs, which will increase the tendency to inconsistent performance. It is noted that the instantaneous trip ratio can be varied to obtain, for example, discrimination between circuit-breakers, but the versatility and usefulness of this feature are considerably restricted if the adjustment cannot be made on site. The curve given in Fig. 7 is largely unsuitable for motor protection, since starting currents of up to eight times full load and starting times of 4–5 sec are frequently encountered; thermal overloads may possibly meet such conditions.

From Section 5.4 it would appear that little can be gained financially in cases where back-up fuses are required. Furthermore, when comparing the initial costs of fuse and circuit-breaker installations, the expense of checking the prospective fault capacity of the system as well as the suitability of any required back-up fuses must be considered.

Mr. J. A. F. Harvey (*at Chester*): The impression may have

been created that the larger type of circuit-breaker requires attention and maintenance after interrupting one full-value short-circuit and is mechanically tested to only 500 operations. However, a modern medium-voltage circuit-breaker will perform up to a dozen times on its rated short-circuit duty on one set of contacts and is capable of more than 15 000 operations by power closing without need of repair. The 15 000 operations suggested for the life test of the miniature circuit-breaker seem low. I would suggest 50 000–60 000 operations and wonder how this compares with the duty demanded of American circuit-breakers.

On the question of the correct application of a miniature circuit-breaker with respect to a fuse, fuse-switch and/or contactor, the determination of the short-circuit current at the points in the distribution network is all-important, and lack of knowledge of this is a contributing factor to the reluctance to use miniature circuit-breakers. More time could be devoted to exploring positions where miniature circuit-breakers could be used, and I am sorry that tests have not been done with a prospective 25 MVA applied to a test network to show how the maximum current is reduced to a value which these units will handle. Such information would have inspired confidence. In some American circuit-breakers, compartments are fitted with reactor coils to reduce the prospective maximum current.

It seems to be wrong that the design of the miniature circuit-breaker is complicated merely because it is occasionally needed for d.c. circuits. Apart from the specialized use in the field of transport, the vast majority are required for a.c. supplies. Thus, a well-designed a.c. circuit-breaker could do without a blow-out system and would therefore be cheaper.

I think that the sealed oil dashpot has considerable advantages over the normal type of dashpot. The desensitizing coil described must affect the inverse characteristics, and I would appreciate more information.

Most of the circuit-breakers on show, except for two or three derived from American designs, appear to have a slow making mechanism. This seems to be a retrograde step, since even the ordinary lighting switch is spring-toggle operated. The difficulty described in the paper on making against short-circuit conditions would be eased with a good spring-toggle action.

Mr. D. A. Picken (*at Chester*): The miniature circuit-breaker is most vulnerable from the safety aspect. I know it is possible for a fuse to be misused and it is equally possible for a circuit-breaker to be tied in, but spiders and other small animals are most efficient at clogging small mechanisms.

I have recently carried out surveys of similar devices (earth-leakage circuit-breakers), and more than 90% of these have failed to operate under normal service conditions; one can hope for nothing better from apparatus made to the same specifications.

The idea of a miniature circuit-breaker is excellent, and I have seen at least one make (Continental) which could be used to replace an ordinary fuse insert and had a rupturing capacity of about 15 mVA; if made to a high degree of accuracy it had good cut-off values. If this is the standard of thing we are to make the uses for it are considerable, but we cannot afford to develop the old type of circuit-breaker unless we make striking technical advances in production methods.

The authors make the point that fuses have a clear-to-running ratio of the order of 1·6. There are plenty of fuses which do better than this, and the demonstration showed that a circuit-breaker continued to carry 150%, which is rather worse than some fuses.

Messrs. H. W. Wolff and **T. G. F. Atherton** (*in reply*): Throughout all the discussions the problem of rupturing capacity has been the concern of most speakers in some way or another, but we feel that excessive emphasis has been placed on this point. Determination of the prospective fault current at individual locations is, of course, out of the question, but we are convinced that this is unnecessary in view of the low fault level of sub-circuit networks. This is conclusively proved by the extensive use of miniature circuit-breakers, not only in the United States—where, it is argued, the phase-to-neutral voltage is only 125 volts—but also in New Zealand, Australia, South Africa and the Continent, where voltages similar to those in this country are employed.

Mr. Ellis and Mr. Funke appear to worry at the uncertainty as to when to back up miniature circuit-breakers. This point hardly arises, or—more correctly—is automatically taken care of, since every group of miniature circuit-breakers—in the same way as a group of fuses—will be backed up by a fuse or a larger circuit-breaker. There is no question of backing up each circuit-breaker in this manner, which would, of course, increase the cost of installation. For the same reasons, we cannot agree with Mr. Jacks that, owing to the calculated high fault current which may exist in isolated instances, the application of miniature circuit-breakers for sub-circuit protection is *ipso facto* limited. We feel that their field is as wide as, if not wider than, that of equivalent rewirable fuses.

Mr. Ellis also queries the efficiency of miniature circuit-breakers after short-circuit: various standard specifications in existence in other countries specify stringent tests following rupturing-capacity testing to ensure that their efficiency has not been substantially impaired. These tests relate to voltage drop, temperature rise, time/current characteristic, etc., and are carried out on the samples which have been short-circuit tested.

We would inform Mr. Dighton that, in the majority of designs, ambient temperature compensation has not been attempted, since for most applications it has been found quite unnecessary. On the other hand, some designs incorporate a compensating device, and others simply swamp the ambient-temperature effect.

In reply to Mr. Funke, it is usual to apply derating factors to miniature circuit-breakers when they are used in conditions of high ambient temperature, particularly in tropical climates, in the same way as that adopted for fuses. Under severe tropical conditions the plating of components and design of enclosures may have to receive special attention.

We thank Mr. Rumfitt for drawing attention to some of the inherent advantages of miniature circuit-breakers regarding routine testing. He also refers to the feature of interruption at current zero: we have found that, although under most circumstances interruption will take place at current zero, tests have shown that it is possible to obtain cut-off or, more correctly, current chopping.

We are indebted to Mr. Tattley for his interesting details of various applications of miniature circuit-breakers.

Mr. Ellis refers to the frequency with which fuses in an installation might be expected to blow. An extensive survey of many installations would be necessary before any reliable answer could be made. However, we believe that the frequency and cost of fuse blowing is greater than is generally appreciated. This is supported by the example quoted in Section 7.2; in that instance, the total extent of fuse blowing, although recorded, was quite unknown until an investigation was carried out following our inquiry.

Electrical practice in the United States has for many years tended towards the use of miniature circuit-breakers. It is, however, interesting to find that in installations where fuses are preferred for their low initial cost, greater use is made of panel-boards having both switched and fused outgoing ways. There is therefore justification for the comparisons suggested by Mr. Harbottle, and even for this reason alone there may be economic justification in adopting the use of m.c.b. panels.

PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

Part A. POWER ENGINEERING, FEBRUARY 1957

CONTENTS

Declaration on Fair Copying.—Within the terms of the Royal Society's Declaration on Fair Copying, to which The Institution subscribes, material may be copied from issues of the *Proceedings* (prior to 1949, the *Journal*) *which are out of print and from which reprints are not available.* The terms of the Declaration and particulars of a Photoprint Service afforded by the Science Museum Library, London, are published in the *Journal* from time to time.

Bibliographical References.—It is requested that bibliographical reference to an Institution paper should always include the serial number of the paper and the month and year of publication, which will be found at the top right-hand corner of the first page of the paper. This information should precede the reference to the Volume and Part.

Example.—SMITH, J.: "Reflections from the Ionosphere," *Proceedings I.E.E.*, Paper No. 3001 S, December, 1954 (102 A, p. 1234).

Published by The Institution, Savoy Place, London, W.C.2. *Telephone:* Temple Bar 7676. *Telegrams:* 'Voltampere, Phone, London.'
Printed by Unwin Brothers Limited, Woking and London.